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NAIADQ, A COMPUTER PROGRAM FOR CALCULATING REACTIVITY TRANSIENTS IN LOW POWER EXPERIMENTAL WATER REACTORS

by

A. Dalton

ABSTRACT

The computer code NAIADQ is designed to simulate the course and consequences of non-destructive reactivity accidents in low power, experimental, water-cooled reactor cores fuelled with metal plate elements. It is a coupled neutron kinetics-hydrodynamics-heat transfer code which uses point kinetics and one-dimensional thermohydraulic equations.

Nucleate boiling, which occurs at the fuel surface during transients, is modelled by the growth of a superheated layer of water in which vapour is generated at a non-equilibrium rate. It is assumed that this vapour is formed at its saturation temperature and that it mixes homogeneously with the water in this layer.

The code is written in FORTRAN IV and has been programmed to run as a catalogued procedure on an IBM operating system, such as MVT or MVS, with facility for the inclusion of user routines.

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COMPUTER CALCULATIONS; EXCURSIONS; FINITE DIFFERENCE METHOD; FUEL PLATES; HEAT TRANSFER; HYDRAULICS; HYDRODYNAMICS; N CODES; NUCLEATE BOILING; PWR TYPE REACTORS; REACTIVITY; REACTIVITY INSERTIONS; REACTOR KINETICS; SIMULATION; TRANSIENTS; TWO-PHASE FLOW

CONTENTS

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1. INTRODUCTION

1.1 Objective of the Simulation

A major problem in the safety evaluation of a fission reactor is the prediction of the time history of the coolant density during unsteady reactor operation. This time history must be accurately known in order to calculate the net reactivity feedback at any instant during a power excursion. Without a qualitative and quantitative understanding of the coolant density changes, the detailed transient behaviour of the reactor system cannot be predicted with confidence.

The objective of the present work was to develop a code which could simulate the dynamic behaviour of the water coolant during power transients in experimental, water-cooled nuclear reactors; the calculated time history of the coolant density was used to determine the net reactivity feedback which influences the transient behaviour of the reactor system during the power excursion. This analysis entails the description of the transient heat transfer from the fuel to the coolant, the generation of steam voids in surface nucleate boiling, and the associated reactivity feedback accompanying these phenomena.

The code has been used by Dalton [1983a] to simulate the reactivity transients measured on the experimental fission reactor SPERT II [Johnson et al. 1965]; Dalton [1983b] has also used the code to simulate a set of laboratory experiments in which water contained in a vertical annulus was heated by electrical power pulses [Singer 1967]. Agreement was obtained with both sets of experimental data.

1.2 Principles of the Calculations

In the NAIADQ code, the reactor core is represented as a single fuel* channel operating in the mean core flux with mean core coolant flow. The physical behaviour of the coolant in this channel is modelled as a function of time and axial location in terms of a set of equations [Turner and Trimble 1978] for the conservation of the mass of the vapour and the mass, momentum and energy of the water-vapour mixture at a number of nodal points along the flow path. In this model, it is assumed that the two phases mix homogeneously and have equal pressures and velocities, and that the vapour is always in the saturated state, the liquid phase being allowed to superheat. Coupled to these equations is a detailed heat transfer model which determines the partitioning of the energy generated in the fuel between the fuel element and the coolant

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* 'fuel' is used in this report to denote 'fuel element' hence reference to 'fuel surface' implies 'fuel clad surface, etc.

fluid. Heat transfer options in the code cover the phenomena of boiling and non-boiling both with and without coolant flow.

In the calculations, a transient is initiated by the specification of a step increase in the core reactivity at time zero. The thermal changes produced in the fuel plates and the adjacent coolant by the consequent increase in the fission power within the fuel are calculated numerically by the code at successive time steps throughout the transient. At each time step, the changes produced in the excess core reactivity by the various feedback mechanisms (thermal expansion and Doppler broadening for the fuel, density changes for the coolant and neutron spectral effects) are estimated and the power change in the next time step is calculated.

The energy generation rate in the fuel is calculated from the instantaneous values of the excess core reactivity using a point reactor kinetics model. The excess core reactivity at any instant is equal to the sum of the initial imposed excess reactivity and the changes produced in the core region up to that instant by the energy input to the system.

1.3 Method of Solution

The conservation equations are represented as a set of partial differential equations which are solved numerically using a first order finite difference method, the space-time mesh for the latter being defined by the nodal points and the sequential time steps used in the calculations. Because the method is stable for all time step sizes, the latter are continuously varied in response to criteria needed to ensure the required accuracy in the calculations. The solution to these equations, which forms the bulk of the calculations done by the NAIADQ code, yields the fuel surface temperature and the state properties of the coolant at each nodal position at each time step.

During an actual experimental power transient initiated under the above conditions, steep temperature gradients can be established in the coolant normal to the fuel plate surface, with the result that boiling could occur at the fuel plate/coolant interface long before the bulk coolant temperature reached saturation. The effects of this temperature gradient on the vapour generation and reactivity feedback are estimated from the data obtained from the one-dimensional thermohydraulics data, using a model based on that of Connolly [1977]. Details of these calculations are presented in Sections 3 and 4.

1.4 Code Design

A modular structure is used in the NAIADQ code in which both the mathematical models and execution procedures are collected into sub-routines. Dummy routines are also included in the code to provide the user with a simple means of exercising control over the calculations at all stages of the transient simulation. For efficient utilisation of computer time, load modules on all these routines are contained in a system library as a partitioned data set.

To simulate a power transient with the code, the test conditions are specified in terms of both input data (Section 6) and user routines (Section 5). The latter are written as FORTRAN source decks, examples of which are given in the sample problem (Section 7). These routines are substituted for the dummy routines, using the catalogue procedures described in Section 5. The composite code is then used to solve the particular problem.

A dummy routine is included to enable the user to store large numbers of data as a 'dump' file in a form suitable for direct input to a number of print and plot programs (Section 5). Notations used in this report are listed in Section 10.

2. HISTORICAL BACKGROUND

Historically, consideration of non-equilibrium two-phase flow in the safety of nuclear reactors has been associated with attempts to simulate the rapid depressurisation that could occur in a pressurised water reactor (PWR) loss-of-coolant accident (LOCA). These simulations were concerned with vapour generation in a liquid which becomes superheated as a consequence of a reduction in its saturation temperature produced by the rapid drop in pressure. This can occur uniformly throughout the volume of the coolant, e.g. at low power and zero flow. The NAIADQ code has been written to describe reactivity transients in which the vaporisation occurs as a consequence of the superheating of the coolant produced by a rapid increase in the surface temperature of the fuel elements. Such calculations are concerned with rapidly changing, steep temperature gradients normal to the fuel clad surface at almost constant pressure. The novelty in the treatment of this problem by the NAIADQ code is the type of modelling, which extends the use of the vapour generation relations used in the depressurisation accidents to the description of the consequences of reactivity transients. For this reason, a historical account is given of the models and assumptions used in the depressurisation codes.

It has long been recognised that a rational non-equilibrium two-phase flow model of the coolant in the fuelled region of the core is required to describe the flow excursions that can occur in PWRs when subjected to large accidental changes in either the coolant pressure or the fission power. Zuber [1967] described a model in which the effects of thermal non-equilibrium are accounted for in terms of an explicit rate of vaporisation, in which one phase is at saturation and the other can be either superheated or subcooled. The dynamic and propagation characteristics of the resultant boiling mixture are described by a set of four equations which comprise the conservation of the mass of either phase plus the conservation of the mass, momentum and energy of the mixture.

Many codes based on sets of equations of this type have been written to describe depressurisation accidents in which the bulk coolant becomes rapidly superheated as a consequence of the sudden fall in pressure. The major differences between the various codes lie in the assumptions made in the derivation of the vapour source term. Attempts were made by Saha and Zuber [1978] to base the formulations on the microprocesses involved in the formation and growth of bubbles in surface boiling, but uncertainties in the parameters involved have so far prevented a rigorous formulation in these terms. A summary of some of the models is given below.

Rasmussen et al. [1974] used separate mass balance equations for each phase plus equations for the mixture momentum and energy in which the flow was assumed to be homogeneous. Their vapour generation equation was based on conduction-controlled heat transfer at the liquid-vapour interface and was proportional to $(T_L - T_S)^2$. The two-dimensional drift-flux model (SOLA-DF) of Hirt and Romero [1975] included an inter-facial shear relation between the phases. It was assumed that the rate

drift-flux model (SOLA-DF) of Hirt and Romero [1975] included an inter-facial shear relation between the phases. It was assumed that the rate of vaporisation was proportional to $A(\rho_{SV} - \rho_V)$, where A is the area of contact between the two phases. Rivard and Torrey [1975] used a general multifield model in which slip was included and the vapour assumed to be in a saturated state. The rate of vaporisation was assumed to be proportional to $A(T_L - T_S)$. Good agreement with the experimental data of Edwards and O'Brien [1970] was obtained in all the above investigations.

In his DRUFAN code, Wolfert [1976] used a similar hydraulic model to that of Rasmussen et al. His vapour generation rates were based on bubble growth rates controlled by heat transfer correlations which contain an expression that was proportional to $\alpha^{1/2}(T_L - T_S)$ for relative

motion between the bubbles and the liquid and to $\alpha^{1/3}(T_L - T_S)^2$ for no relative motion. Good agreement with experiments was obtained but the bubble concentration required (5×10^9 m^{-3}) appears to be unreasonably large.

In the HUBBLE-BUBBLE II code, Martin [1978] used a set of three equations for the conservation of the mass momentum and energy of a single component, two-phase fluid. The vapour generation rate was initially controlled by the number of bubbles formed when the pressure fell below the local saturation level. Subsequent growth was determined by conduction-controlled heat transfer to the bubble surface which resulted in the evaporation of the liquid into the bubbles. It was assumed that no heat was transferred directly to the bubble. The instability inherent in the explicit form of Martin's solution limited the duration of the simulation but, within the time scale simulated (300 ms), good agreement was obtained with blow-down experiments in simple straight pipes.

3. DETAILS OF THE NAIADQ CALCULATIONS

The hydraulics equations constitute the basis of the calculations; these are solved numerically using a finite difference method. The equations describe the one-dimensional time-dependent response of the coolant flow, pressure, enthalpy and quality at a number of axial points (nodes) along the flow path to an imposed time-dependent axial distribution of power. The latter, produced by the generation of fission energy in the fuel, is calculated, using point reactor kinetics equations, from an initial step in the core reactivity, and from subsequent reactivity feedback effects produced by changes in the fuel and coolant temperatures.

Because this one-dimensional description deals only with the mean fluid properties averaged over the cross-sectional area of the flow path at any axial point, the phenomenon of nucleate boiling at the heated surface is described explicitly, the vapour associated with surface nucleate boiling being assumed to be generated in an expanding superheated layer of liquid at the fuel-coolant interface (Section 3.3). This model is coupled to the thermohydraulics calculations, data from the latter being used to determine the changing thickness of the superheated layer, the vapour generation rate and its reactivity feedback effects.

To simulate a reactivity-induced transient, the neutron kinetics equations [Clancy 1983] are solved to determine the reactor power after

a small time interval following a step increase in the excess core reactivity during reactor operation at a low power steady state (specified as input to the code). The conservation equations are then solved to determine the dynamic response of the coolant to this power increment after an equally small time interval. From the calculated changes in the core properties, the reactivity feedback effects are estimated. This cycle is repeated for successive time steps of the finite difference calculations, core reactivity being updated by the sum of the feedback effects produced in the preceding time interval. When surface nucleate boiling arises, a calculation of the vapour generation rates is made at each time step and the associated reactivity effects included in the feedback estimates. The lengths of the time steps are chosen to limit the magnitude of the fractional changes which can occur in P and H within the time steps, hence large time steps are used when the coolant conditions are changing slowly and small time steps when the changes are rapid. The various stages are described in more detail below.

3.1 The Hydraulics Model

The conservation equations describing the dynamic response of the coolant fluid in the flow path are one-dimensional in the axial direction. The properties of the fluid are expressed in terms of its local properties averaged over the flow area at a number of axial locations (nodes) along the flow path. The coolant behaviour is represented by the following set of conservation equations at each nodal position [Turner and Trimble 1978]:

(i) Vapour Mass

$$\frac{\partial (C\rho)}{\partial t} + \frac{1}{a}\frac{\partial (CW)}{\partial z} = \Gamma \qquad (1)$$

(ii) Mixture Mass

$$\frac{\partial \rho}{\partial t} + \frac{1}{a}\frac{\partial W}{\partial z} = 0 \qquad (2)$$

(iii) Mixture Momentum

$$\frac{1}{a}\frac{\partial W}{\partial t} + \frac{1}{a}\frac{\partial M}{\partial z} + \frac{\partial P}{\partial z} + F + \rho g \sin\theta = 0 \qquad (3)$$

(iv) Mixture Energy

$$a\frac{\partial}{\partial t}\left(\rho H - P + \frac{M}{2a}\right) + \frac{\partial E}{\partial z} - pq + Wg \sin\theta = 0 \qquad (4)$$

In the two-phase state, it is assumed that there is no 'slip' between the phases, hence the mean properties of the vapour-liquid mixture are represented as either the volume average (using the vapour void ratio α) or the mass average (using the steam quality C) of the local vapour and liquid values.

The equations used to describe the vapour generation rates, heat fluxes and frictional pressure gradients used in the above equations are given below.

3.2 Heat Transfer

Heat transfer between the fuel element and the coolant is determined by such local conditions as fuel surface temperature, rate of coolant flow and pressure, and options are available in the code to calculate the rate of heat transfer in the regimes of conduction, convection and surface nucleate boiling under both flow and no-flow conditions (the calculation is terminated when critical heat flux conditions occur).

The heat flux, q, from the fuel element to the coolant is described in terms of an overall heat transfer coefficient h_T, such that

$$q = h_T(T_F - T_L) \tag{5}$$

where

$$h_T = h_F\, h_{FS}/(h_F + h_{FS}) \tag{6}$$

and the relation between the rate of energy generation in the fuel and that transferred to the coolant is determined from

$$q = Q - A\, dT_F/dt \tag{7}$$

The various options available in the code for the surface heat transfer coefficient h_{FS} are described below. Using the appropriate coefficient in conjunction with the above relationships, the fuel clad surface temperatures and heat flux into coolant at each nodal location are calculated in each time step, these data then being substituted into the hydraulics equations.

3.2.1 Non-boiling heat transfer

For zero or low mass flow (Re < 2000), heat is assumed to be transferred by conduction, a standard model based on slab geometry and an exponentially rising fuel surface temperature being used (see Appendix A).

$$h = \kappa B^2 S/(B S/\tanh(B S) - 1) \quad (8)$$

where $$B = (\rho c/\kappa \tau_0)^{1/2} \quad (9)$$

For turbulent flow (Re > 2000), a number of forced convective surface heat transfer correlations are used, each having the form

$$h = K(\kappa/De)\ Re^n\ Pr^m \quad (10)$$

where the value of the constant K and the indices n and m depend on the option used (Appendix A).

3.2.2 Boiling heat transfer

For pool boiling, the surface heat transfer correlation of Forster and Zuber [1955] is used:

$$h_{NB} = 0.0015\ (\kappa/R)\ Re^{0.62}\ Pr^{0.33} \quad (11)$$

where Re and Pr are the Reynolds and Prandtl numbers for the 'flow system' associated with the bubble agitation in the superheated layer at the fuel-coolant interface. The temperature at which the heat transfer for pool boiling exceeds that for the nonboiling mechanisms is called the 'trigger' temperature. For flow boiling, the interpolation formula of Bergles and Rohsenow [1964] is used, and a correlation from Redfield [1965] is used to estimate the critical heat flux. These relationships are described in more detail in Appendix A.

3.3 Vapour Generation

Under rapid transient conditions, the fuel surface temperature can exceed the bulk coolant temperature by a large margin. Because the flow channel is represented only in the axial direction in the finite difference calculations, a simple analytical representation of the steep temperature gradients in the coolant normal to the fuel surface is used to estimate the effects of surface boiling. From the time t_1 that the fuel surface temperature first exceeds the local saturation temperature of the coolant, it is assumed that a superheated layer of liquid is generated at the fuel-coolant interface which increases in thickness as the heat to the coolant increases [Connolly 1977]. It is also assumed that the temperature of the liquid in this layer is equal to that of the heat surface and that it absorbs the total heat flux. The distance moved by the boundary layer up to time t_1 is given by

$$\chi(t) = \int_{t_1}^{t} q\ dt \Big/ \int_{T_{L1}}^{T_\chi} \rho(T)\ c(T)\ dT \quad (12)$$

where T_{L1} is the coolant temperature at time t_1.

The integrals in this equation are solved explicitly and the values of $\chi(t)$ evaluated using parameters derived from the finite difference calculations. When the temperature of the superheated water reaches the trigger level, the bubbles formed at the surface of the fuel begin to grow, become detached, then rapidly increase in size. The rate at which vapour is generated is assumed to be given by the formula [Rivard and Torrey 1975]:

$$\Gamma_\chi = \lambda_N \alpha^{2/3} (1 - \alpha) (T_S R_u)^{1/2} (T_\chi - T_S)/T_S \qquad (13)$$

To produce vapour when the trigger temperature is exceeded, a 'seeding' value for α must be specified as input to the code.

3.4 Reactor Kinetics

The time-dependent behaviour of the reactor power is determined by solving the reactor kinetics equations using the KINET subroutine described by Clancy [1983]:

$$\frac{d\phi(t)}{dt} = \left[k(t) (1 - \beta) - 1 \right] \frac{\phi(t)}{\ell} + \sum \lambda_i C_i(t) \qquad (14)$$

$$\frac{dC_i}{dt} = k(t) \beta_i \frac{\phi(t)}{\ell} - \lambda_i C_i \qquad (15)$$

The time-dependent multiplication factor $k(t)$ is coupled to the temperature distribution via the heat transfer correlation equation and is given by

$$k(t) = k_0 + \sum_0^t \Delta k(t) \qquad (16)$$

The values of $\Delta k(t)$ are calculated at each nodal point along the flow path in each successive time step cycle. The nodal contributions are axially weighted and summed to yield the total value of Δk from zero up to time t. In the non-boiling regime, the effects include fuel plate expansion, moderator expansion and neutron temperature changes in the core region:

$$\Delta k(t) = B_1 \Delta T_F + B_2 \Delta T_L + B_3 \Delta \rho_L / \rho_0 \qquad (17)$$

To calculate the contribution to Δk from density changes in the coolant in the boiling regime, an explicit representation for the mean core density is used:

$$\rho(t) = \alpha'(t)\rho_v + (1 - \alpha'(t)) \left[\frac{\chi(t)}{S} \rho_\chi(t) + \left(1 - \frac{\chi(t)}{S}\right) \rho_L(t_1) \right] \quad (18)$$

where $\alpha'(t)$, the void ratio for the whole core, is related to that calculated in the thermohydraulics calculation for a single channel by a 'weighting' factor ω, which takes account of the spatial variation in flux shape within the core. Reactivity at any subsequent time is obtained from

$$\Delta k = B_3 [\rho_o - \rho(t)]/\rho_o \quad (19)$$

which, to a first order approximation, reduces to

$$B_3 \left[\omega\alpha + (1 - \omega\alpha) \frac{\chi}{S} \frac{\Delta\rho_\chi}{\rho_o} + \left(1 - \frac{\chi}{S}\right) \frac{\Delta\rho_L}{\rho_o} \right] \quad (20)$$

3.5 Frictional Pressure Gradient

The frictional pressure gradient term F is the sum of contributions from wall friction and pressure losses due to local effects arising from fittings and cross-sectional changes along the pipe, and is given by

$$F = \rho u | u | (2f/De + Ke/\Delta z) \quad (21)$$

where Ke is the coefficient representing the sum of local pressure losses.

The code contains expressions for the Fanning friction factor f, covering the range from near zero flow up into the turbulent region, including an optional boiling wall friction factor [Trimble and Turner 1976]. In the calculation, the two-phase state is assumed to be homogeneous; the viscosity of the mixture is expressed as the mean value of the vapour-liquid mixture

$$1/\mu = C/\mu_{SV} + (1 - C)/\mu_L \quad (22)$$

4. FINITE DIFFERENCE REPRESENTATION

4.1 Derivation of the Equations

For numerical stability, the spatial derivations of the independent variables (W, P, H and C) are evaluated at the end of each time step [Trimble and Turner 1976]. The dependent variables are expressed in terms of first order Taylor expansions, for example

$$\rho' = \rho + \frac{\partial\rho}{\partial t} \Delta t \quad (23)$$

and their derivatives are defined in terms of the basic variables

$$\frac{\partial \rho}{\partial t} = \frac{\partial \rho \partial X}{\partial X \partial t} = \frac{\partial \rho \partial W}{\partial W \partial t} + \frac{\partial \rho \partial P}{\partial P \partial t} + \frac{\partial \rho \partial H}{\partial H \partial t} + \frac{\partial \rho \partial C}{\partial C \partial t} \tag{24}$$

where X is the vector representation of the four basic variables W, P, H and C.

In the derivation of the finite difference equations, the above scheme was used in conjunction with the assumption that the set of nodes n defining the spatial mesh were related to the axial distance z along the flow path by

$$z_1 < z_2 < \ldots . z_i < \ldots < z_n \tag{25}$$

and the finite time step was Δt.

4.2 Conservation Equations

Using the relationships derived above, the algebraic forms of the conservation equations can be written in finite difference forms as follows:

(a) Mass Equation

$$\frac{a_j}{\Delta t}\left(\frac{\partial \rho}{\partial X}\right)_j (X_j' - X_j) + \left[\frac{W_j' - W_k'}{z_j - z_k}\right] = 0 \tag{26}$$

where $k = j + 1$, $j = 1$ to $n - 1$.

(b) Momentum Equation

$$\frac{W_j' - W_j}{a_j \Delta t} + \frac{P_j' - P_k'}{z_j - z_k} + \frac{1}{a_j}\left[\frac{M_j' - M_k'}{z_j - z_k}\right] + \frac{F_j W_j'}{2W_j} - \frac{F_k W_k'}{2W_k} - \rho_j g \left[\frac{y_j - y_k}{z_j - z_k}\right] = 0 \tag{27}$$

where $k = j - 1$, $j = 2$ to n.

(c) Energy Equation

$$\frac{a_j \rho_j}{\Delta t}(H_j' - H_j) - H_j\left[\frac{W_j' - W_k'}{z_j - z_k}\right] - \frac{a_j}{\Delta t}(P_j' - P_j) + \left\{E_j + \left(\frac{\partial E}{\partial X}\right)_j \left[\frac{X_j' - X_j}{z_j - z_k}\right] - E_k - \left(\frac{\partial E}{\partial X}\right)_k \left[\frac{X_k' - X_k}{z_j - z_k}\right]\right\} + \left(\frac{\partial M}{\partial X}\right)_j \left[\frac{X_j' - X_k'}{2a_j \Delta t}\right] - p_j q_j' + w_j g \left[\frac{y_j - y_k}{z_j - z_k}\right] = 0 \tag{28}$$

where $k = j + 1$ if $W < 0$

$k = j - 1$ if $W \geq 0$.

(d) Vapour Mass Equations

Substituting for the density derivative from the mass equation before transforming leads to

$$\frac{a_j \rho_i}{\Delta t}(C'_j - C_j) - C_j\left[\frac{W'_j - W_j}{z_j - z_k}\right] - \left\{\Lambda_j + \left(\frac{\partial \Lambda}{\partial X}\right)_j \left[\frac{X'_j - X_j}{z_j - z_k}\right] - \Lambda_k - \left(\frac{\partial \Lambda}{\partial X}\right)_k \left[\frac{X'_k - X_k}{z_j - z_k}\right]\right\}$$

$$- a_j \left\{\Gamma_j + \left(\frac{\partial \Gamma}{\partial X}\right)_j (X'_j - X_j)\right\} = 0 \qquad (29)$$

where $k = j + 1$ if $W < 0$

$k = j - 1$ if $W \geq 0$.

4.3 Temperature and Heat Transfer at the Fuel Surface

The heat flux q' is expressed as a first order Taylor expansion

$$q' = q + \frac{\partial q}{\partial X}(X' - X) + \frac{\partial q}{\partial T_{FS}}(T'_{FS} - T_{FS}) \qquad (30)$$

Combining this equation with the fuel model equations (5), (6) and (7), linear expressions for q', T'_{FS} and T'_F are derived in terms of X':

$$q' = D_0\left[D_1 + \frac{\partial q}{\partial X} X'\right] \qquad (31)$$

$$T'_{FS} = D_2\left[D_3 + \frac{\partial q}{\partial X} X'\right] \qquad (32)$$

$$T'_F = D_4\left[D_5 + \frac{\partial q}{\partial X} X'\right] \qquad (33)$$

Equation (31) is used to eliminate q' from the hydraulic energy equation (28). X', which is obtained from the hydraulic solution, permits the determination of T'_{FS} and T'_F from equations (32) and (33). $D_0 \ldots D_5$ are parameters containing the numerical derivatives at the start of the time step.

4.4 Boundary Conditions

In the present finite difference scheme, two boundary conditions are required for the equations of mixture mass and momentum throughout the simulation of a transient and independent of the direction of fluid

flow. These may be specified in terms of either the pressure or the flow rate at either end of the flow path. For the equations of mixture energy and vapour mass, boundary conditions are required only when the direction of flow is inward. For these equations, the number of boundary conditions can be 0 (outward flow at both ends), 2 (inward flow at one end, outward at other end) or 4 (inward flow at both ends).

During a transient, the number of boundary conditions required can vary, depending on changes in the flow direction of the coolant at the end of the flow path. When flow reversal occurs, the code automatically adjusts the number of boundary conditions required. The details are given in Appendix B.

4.5 Time Step Control

The magnitudes of the time steps used in the NAIADQ calculations are selected within the code on the basis of the maximum fractional changes in either P or H that the user considers to be acceptable in a single time step [Trimble and Turner 1976]. This allows large time steps to be used when conditions are changing slowly and small time steps when changes are rapid, thus optimising the central computer processing time. The data relating to the selection of the time step size are specified as standard input to the code (Section 6); in addition to the maximum permissible fractional change in P and H, the user must also specify the maximum and minimum time steps and the maximum increase allowed within the time step at any stage.

5. PROGRAMMING DETAILS

5.1 General Principles

The routines included in the code and their sequence of operation are shown in Figure 1. Numbers 1 to 12 in Figure 1 denote the order in which the routines are called in NAIADQ; numbers 4 to 11 represent the time step cycle and 6 to 10 the time repeat cycle in which the time step size is determined.

The majority of the routines are standard to the code and cover both mathematical modelling and procedures for the execution and control of the calculations; none of them are accessible to the user. These routines are described in Sections 5.3 and 5.4 and included in this report for information only. The dummy routines are included in the code to provide the user with a simple and straightforward procedure for selecting the type of transient to be simulated, for computing and writing additional output, for printing and plotting, and for imposing time-dependent boundary conditions. They also provide the flexibility

for future expansion of the capabilities of the code while leaving the main body of the program intact.

All routines are written in FORTRAN IV, the source decks being located as partitioned data sets. Load modules of all the routines are also stored as a partitioned data set. The details of the routines and their execution are described below.

5.2 Dummy Routines

Calls to the dummy routines are included in the NAIADQ subroutine at stages which provide the user with a wide degree of control of the transient calculation (Figure 1). In the standard code, each dummy routine consists of three cards which, for TROPIN, would be

```
SUBROUTINE TROPIN
RETURN
END
```

A subroutine with the same name, written in FORTRAN IV by the user, is included in the NAIADQ calculation by means of the catalogued procedure NAIADCLG of the NAIAD code [Trimble and Turner 1976]. The latter compiles and links the user's routine to the main program, then executes the resultant composite code.

Many of the variables used in the standard routines are contained in the common blocks described in Appendix D. The appropriate common blocks can be included in the user's routine by inserting a statement of the form CINSERT COM1, COM2, etc., where COM1 and COM2 are the names of the selected common blocks. The statement must begin in column 1. Because all variables and arrays in the code are double precision, the statement

```
IMPLICIT REAL*8 (A-H,O-Z)
```

must be included in each user's routine also; this is generated by the statement

```
CINSERT R*8
```

Details of all the dummy routines are given below and examples of their application are explained in the sample program (Section 7). Printouts of the routines used in the sample problem are given in Appendix C2.

TROPIN Statements determining the input requirements for a specific transient, such as the power level for a power transient simulation or reactor kinetics data and reactivity feedback coefficients for a reactivity-induced transient simulation are inserted in this routine. A

header record for any output data records (Section 5.5) is written by inserting a call to the subroutine WDUMP.

TRDUMP Any output data which the user wishes to save can be written on a dump file by inserting a call to TDUMP in this routine. Changes can be made at each time step to parameters which do not affect the determination of the time step size, such as the calculation of the reactivity feedback effects in a reactivity-induced transient simulation.

TRAPON A user routine with this name allows changes to be made at each time step which is involved in the determination of the time step size, e.g. changes in the mean reactor power and the explicit formulation of boundary conditions (Appendix B).

TRTEST This routine allows the user to impose additional time step controls, such as an upper limit on the allowable increase in the fuel surface temperature.

TRDATA This routine is called at the end of a transient calculation. It can contain any instructions for final output, such as total energy generated during the transient.

5.3 Routines used for Physical Modelling

LSTATE This routine is used to determine the properties of the liquid in both the subcooled and the superheated states, and the properties of the vapour at saturation. Its arguments are

$$P,\ s,\ \rho,\ x,\ (\partial\rho/\partial H)_P, (\partial\rho/\partial P)_H,\ T_L,\ T_S,\ \alpha,\ H_L,\ H_V,\ \rho_L,\ \rho_V,$$

$$s_L,\ s_V,\ (\partial T_L/\partial H)_H,\ (\partial T_L/\partial_H)_P,\ H,\ d\rho_V/dP,\ d\rho_L/dP,$$

$$dH_V/dP,\ dH_L/dP,\ dH/dP,\ k$$

The value of the integer k is used to select the appropriate option:

- k = 0 the properties of the liquid in the subcooled region are obtained,
- k = 1 the properties of the liquid in the superheated region are obtained, and
- k = 2 the properties of the vapour on the saturation line are obtained.

NSTATE This routine uses data obtained from calls to LSTATE to provide the derivatives, with respect to the four basic variables, of all the state properties of the coolant.

FRIC This routine calculates the Fanning friction factor and the frictional pressure drops in each node of the flow path using the assumption of homogeneous flow. The geometrical and physical data of the coolant are obtained from the STATE, FLOW and GEOM common blocks and the viscosities of the liquid and vapour from the routine VISCOS.

VISCOS The arguments are

$$T_L,\ T_S,\ T_{FS},\ \mu_L,\ \mu_v$$

The liquid and vapour viscosities are calculated using the same formulae as the VISCOS routine of the NAIAD code.

SLIP Because homogeneous flow is assumed, there is in fact no slip between the phases, the vapour velocity u_v and liquid velocity u_L being equal. The quantities evaluated by this routine are E, M and WV, the data for the calculation being obtained from the GEOM, STATE and FLOW common blocks.

STRANS AND HTRANS The surface heat transfer coefficient is calculated in HTRANS via STRANS. The call argument list contains the output data h, the heat transfer coefficient selected and a variable THT, the value of which indicates the correlation type (Appendix A). The input data are

$$De,\ p,\ G,\ T_L,\ T_S,\ \rho_L,\ \rho_v,\ C,\ H_L,\ H_{SV}$$

Correlations are included to cover all situations, that giving the largest heat transfer coefficient in the prevailing conditions being selected. The value of the variable THT indicates the correlation used at each time step during the calculations; these correlations are given in Table 1, and referred to in Appendix A. For values of THT less than one, the correlation used in the previous entry to HTRANS is used again.

HTCHEN This routine is based on the model of Forster and Zuber [1955] and is called from HTRANS to evaluate the surface boiling heat transfer correlation h_{NB}. The argument list is

$$h_{NB},\ T_L,\ T_S,\ T_{FS}$$

The details of the calculations are given in Appendix A.

EXPCON This routine calculates the surface heat transfer coefficient associated with transient conduction, based on the model of Bayley et al. [1977]. The argument list is

S, T_L, τ_o

SUPREG In this routine the position of the superheated region is calculated and all input and output data are transferred via the common blocks EXPAND and STATE. The coding in this routine is based on the vapour generation model described in Section 3.

VAPGEN This routine calculates the vapour generation rate Γ. Input is obtained from the common blocks STATE, TEMPS, POW$ and Γ is output via the common block FLOW.

KINDAT This is an additional input routine which handles all of the extra data required for a neutron kinetics calculation plus the reactivity coefficients used in the feedback calculations.

KINET This routine [Clancy 1983] calculates the power, the precursor concentrations C_i', the neutron multiplication factor k' and the energy ξ' generated at the end of the time interval. The input data required for this calculation are

$$k, C_i, \lambda_i, \rho, n_\beta, \beta, \beta_i, \phi, \frac{\Delta k}{k} \text{ or } \frac{\Delta k}{\Delta t}, \Delta t$$

and the output is

$$\phi', C_i', \lambda_i', \xi', k'$$

FEEDBK The reactivity feedback associated with changes in the fuel and the coolant properties is evaluated from the data calculated in the code, using the coefficients supplied by KINDAT. Common blocks utilised are STEP, STATE, TEMPS, EXPAND and KINFED.

5.4 Routines used for Execution and Control

Many of the routines in this group were written originally by Turner and Trimble [1978]. Of these, SCOPY, SOLVE and DSTM44 have been retained unchanged. INPUT, SETMAX, COEFFT, COEFFM and UPDATE were modified to accommodate the heat transfer models which have been added to the code. The routines dealing with the steady-state calculations, STEADR, STEADP and STEADW were adapted from similar routines in NAIAD.

BOUNDS The enthalpy (and quality) boundary conditions required following flow reversal are calculated in this routine. Three options are available, the choice being specified by LBC in the standard input (Section 6):

LBC = 1 integral flow,

LBC = 2 mean node, and

LBC = 3 explicit dependence.

COEFFM This routine is an interface between NAIADQ and COEFFT. The output at each time step is printed at intervals during the calculations specified in the input.

COEFFT The parameters required to evaluate the coefficients of the hydraulic terms in the matrix equations are calculated. The partial derivatives of M, E, WV, VG, ρ, and α are evaluated by repeated calls to SLIP and VAPGEN routines.

COEFFH All the parameters required to evaluate the coefficients of the heat transfer terms are evaluated by repeated calls to the heat transfer routine HTRANS.

DATIM The current calendar date is obtained from this routine; this routine is available from the AAEC's AAE.FORTLIB library.

DSTM44 The block tridiagonal system of 4 × 4 matrices with multiple right hand sides is solved.

FTTGO The remaining CPU time is calculated.

FUEL Steady-state fuel temperatures are calculated.

GRHON The mean density in a segment is calculated.

INPUTZ Most of the input data are read here. The power distribution in the flow path is normalised and a number of variables and arrays are set to their initial values.

MASSEQ The finite difference coefficients in the conservation of mass equation are calculated.

NAIADQ This routine is the mainline of the code; it controls time stepping and output.

SCAN This is an AAEC free format routine [Bennett and Pollard 1967].

SETMAX The matrix equations are set up from the differential equations and boundary conditions.

SOLVE The matrix equations are solved.

SCOPY State variables are copied from node i to dummy node k to facilitate the numerical differentiations done by the COEFFT routine.

SSINIT The equation-of-state tables are read from a sequential data set.

STEADR The required initial states are calculated.

STEADP The steady-state hydraulic difference equations are solved along the flow path.

STEADW The steady-state, zero flow mass and momentum conservation equations are solved along the flow path; for this, the enthalpy at each node is required as input data.

UPDATE The values of the quaternion of variables, W', P', H' and C' are determined at the end of the time step. The new heat fluxes, power to coolant and fuel temperature are also calculated.

VARRAY Core storage is allocated dynamically. This routine is used for the equation-of-state tables.

5.5 Plot Routines

The output from each NAIADQ run may be stored as a dump file on a nominated data set, by calls to WDUMP and TDUMP. This dump file can then be used as input data to a selection of print and plot programs, described by Turner [1982], to facilitate the interpretation of the output data. Its use is illustrated in the sample problem and examples of the plots are given in Figures 2 to 5.

WDUMP The dump file number, NFILE, on the nominated data set and the FORTRAN logical unit number, NU, allocated to the latter can be specified by calls to this routine. The argument list is

NU, NFILE, NHEAD

where NHEAD is the required heading.

TDUMP The variables to be included on the dump file are specified in this routine; the argument list is

NU,TIME,1,A1,N1,A2,N2,.....,AK,NK

where A1,A2,....AK - are variable or array names, and
N1,N2,....NK - are the number of data items to be written for the corresponding variable or array.

Any number of arguments may be supplied.

6. INPUT DATA

6.1 General

Except for the title card, all data are read with the AAEC free input subroutine SCAN [Bennett and Pollard 1967]. The data may be entered anywhere on a line with numbers separated by blanks or commas. Alphabetic comments may be placed among the data and comment cards (identified by an * in column one) may be used, of which no account is taken by the input.

6.2 Title Card

HEAD Title Card.

6.3 Controls

SMIN Minimum time step to be used.

SMAX Maximum time step to be used.

SINC Maximum ratio between successive time steps, e.g. 2 means twice the time step.

TSFP Time after which a full printout will be produced at each time step.

TMAX Maximum time required.

CTAR Target maximum fractional change in P or H for any time step (suggest 0.01).

CMAX Maximum allowable fractional change in P or H for any time step (suggest 0.02).

ALAM Constant in the vapour generation formula.

ALPHO Seeding value of the void ratio.

6.4 Flow Path Data

NODE Number of nodes in the flow path.

SLIP NODE integers, which specify slip relation to be used at each node; only one option available - 1 (homogeneous).

FRIC NODE integers, which specify friction relation to be used at each node; only one option available - 1 (homogeneous).

NS NODE number, for which a printout of data is obtained at every time step (only one number possible).

NP Number of time steps between each full printout.

Z NODE values specifying the axial position of each node from an arbitrary origin, but must be increasing.

Y NODE values of the vertical height.

DE NODE values of equivalent diameter.
If DE(I) is given as zero, it is calculated from A(I) assuming a cylindrical pipe.

A NODE values of cross-sectional area a. If A(I) is given as zero, it is calculated from DE(I) assuming a cylindrical pipe.

SR NODE values of absolute surface roughness.

ORIKE (NODE-1) values of explicit pressure loss coefficients.

POWER Total power generated in the flow path.

HP NODE values of heated wetted perimeters. If HP(I) is given as zero, it is calculated from DE(I) assuming a cylindrical pipe.

CP NODE values of fuel heat capacity; if zero, the generated power passes directly to the coolant.

HF NODE values of fuel heat transfer coefficient h_F.

PD NODE values specifying an equivalent heat flux distribution $P_D(I)$. The given distribution is normalised within the code, so PD(I) = Q(I)/PGENP.

A dashed line is printed in the output after the flow path data are read and printed.

6.5 Boundary Conditions

The following set of data is required at both ends of the flow path.

LBC Joint boundary condition for enthalpy and quality:

1 - integral flow.

2 - mean node.

3 - explicit.

LWP Type of boundary control:

1 - flow.

2 - pressure.

6.6 Initial Coolant Conditions

W mass flow rate.

C quality - specified as 0 because all transients start with coolant in the liquid phase.

P NODE values of axial pressure.

H NODE values of axial enthalpy.

6.7 Data for the Neutron Kinetics and Reactivity Feedback

ELL neutron lifetime.

NBETA Number of delayed neutron groups.

BETALL Total delayed neutron fraction.

PEWR Maximum change in power in each time step.

XNDO Power at time zero.

EXCESK Excess reactivity at time zero.

DKDT Ramp rate of reactivity insertion.

SOURCE Shutdown power in the reactor.

BLO Asymptotic inverse period of the transient.

CORE Number of fuel assemblies in the reactor core.

EXPAN Fuel expansion coefficient.

FDOPL Doppler reactivity coefficient.

CSPEC Neutron spectral reactivity feedback coefficient.

CRHO Coolant density reactivity feedback coefficient.

BCOND Weighting factor from void reactivity feedback.

7. SAMPLE PROBLEM

7.1 Objective

The sample problem is the simulation of a rapid power transient in an experimental SPERT II core [Johnson et al. 1965] in which the initial coolant conditions are zero flow, a uniform axial temperature distribution of 295 K and ambient pressure. The transient is initiated at a core power of about 70 W by a step change in core reactivity of 1.84 $.

This problem has been chosen to illustrate the steps involved in preparing the NAIADQ code to simulate a particular transient and to demonstrate results of the calculations over a wide range of transient heat transfer regimes under the conditions specific to this type of core.

To run the code involves the specification of input data, the writing of special user routines and the use of JCL to execute the composite program. For the thermohydraulics calculations, the standard input data described in Section 6 are written. To simulate the power changes in the selected transient, both the point kinetics routine KINET and the reactivity feedback routine FEEDBK must be included in the calculations. For both of these calculations, additional input will have to be specified, this being done by a call to the KINDAT routine. For monitoring the calculations during the simulation, a selection of the major variables are to be printed out at each time step, and data records of a large number of the calculated variables at each node and at each time step are to be written on a dump file for future use in the plotting routines (Section 5.4).

7.2 Problem Specification and Input Data

The flow path is divided into ten segments by 11 nodes, the locations of which are given in the partial listing of the sample problem output (Appendix C1). The equivalent diameter of the fuelled region of the flow path is 4.63×10^{-3} m, the flow area 2.82×10^{-3} m^2 and the heated wetted area 2.42 m^2. The surface roughness is 2.54×10^{-6} m, the mean heat capacity of the fuel element 1.73×10^{3} J m^{-2} K^{-1} and its mean heat transfer coefficient 2.18×10^{5} W m^{-2} K^{-1}; a uniform axial power distribution is assumed and the initial channel power set at 1 W.

The initial coolant conditions are specified as zero flow, zero quality at all nodes and an inlet pressure of 1.1×10^{5} Pa (node 1), the pressure at all nodes above the inlet being determined by their pressure head. The enthalpy of the coolant at every node is specified as 9.24×10^{4} J kg^{-1} which corresponds to a temperature of 297 K. For the solu-

tion of the finite difference equations, a minimum of two boundary conditions is required. These are specified as input to the code in terms of either a pressure or flow control at either end of the flow path (Appendix B). For an initial zero flow transient, a pressure control boundary condition at both ends of the flow path is chosen to represent a fixed pressure drop across the reactor core. To control the automatic selection of the additional boundary conditions for coolant enthalpy and quality which arise during the transient, the mean node option is used.

To illustrate the effects of vaporisation on the dynamic behaviour of the reactor, two calculations were done: in one, vaporisation was completely suppressed, and in the other the constant in the vapour generation formula was set to 5×10^{-3}. The partial listing in Appendix C1 contains the specification of the latter. For this calculation, a seeding value of 10^{-4} was used for the void ratio.

The input data are given in the partial listing of the sample output in Appendix C1. The comments permitted by the free format routine SCAN are sufficient to make the input data self-explanatory. The variable names used in the printout are defined in Appendix D under the various COMMON block headings. The tabulated channel properties given in the printout following the input specification were produced by statements in the subroutine INPUTZ of the standard code.

The input data for the neutron kinetics and reactivity feedback are listed in the sample printout below the standard data; the text accompanying these data is sufficient to explain them. The tabulated properties of the delayed neutron groups used in the neutronics calculations are produced by statements in the KINDAT routine using data inherent to the NAIADQ code system.

7.3 User Routines

The user routines written for the sample problem are listed in Appendix C2. The routines TRDUMP, TRAPON and TRDATA are included by ENTRY statements in the subroutine TROPIN. The common blocks required for all these routines are included by insertion of a CINSERT card (Section 5.2). The variables belonging to the specified common blocks, listed in the sample printout, are inserted during the PREP step (Appendix C3) in response to the CINSERT statement.

In the TROPIN routine, a call is made to WDUMP to write a header record for the dump file; the FORTRAN unit number and the file number on the data set (NU, NFILE) are read by a call to the free format input

routine SCAN. The data for the routines KINET and FEEDBK are read by a call to the routine KINDAT.

The TRDUMP routine contains statements which, at the end of each time step, update both the channel power XND and the instantaneous power period BL, calculate the total core power POW, print a limited selection of the major variables such as TIME, POW, ENPR (the burst parameter), etc., and transfer data records of a large number of variables to a dump file on a nominated data set for use in the plotting routines (Section 5.5). The reactivity feedback calculations are executed by a call to the routine FEEDBK.

The neutron kinetics are calculated by a call to the KINET routine in TRAPON. If the time step TIMECH for this calculation is smaller than that used in the hydraulics calculations DELT, the latter must be repeated using the value of TIMECH.

The TRDATA routine contains a WRITE statement for the output of the total power on completion of the specified real time for the duration of the simulated transient (TMAX).

7.4 Execution of the Code

The catalogued procedure NAIADCLG is used to compile and link edit the user's FORTRAN source deck to the standard code. As shown in the partial printout (Appendix C3), the EXEC statement for this includes reference to two data sets in the AAEC system, so functions and routines from these libraries that are included in the user's routines are also compiled and link edited. The composite program is then used to do the required calculation. The data set on which the dump file is to be written is also printed out in the JCL statements together with the FORTRAN unit on which it is to be located. The NAIADQ calculation is initiated by the special routine MAINQ which is generated with a CINSERT MAINQ card during the preparation step PREP.

The central processing time taken by the various steps in the execution of the NAIADQ composite program is shown in the printed output following the listing of the JCL instructions.

7.5 Transient Calculation

Selected blocks of numerical data from the sample problem calculations are listed in Appendix C4. Included in this list is the standard output tabulation of the important variables at the 11 axial nodes. In the full printout, these data are printed at intervals of 100 time steps and included to provide a check on the variation of the variables at various stages throughout the calculations; in the sample output

these data are given at 0, 0.576, 1.109 and 1.128 s. Also included is a printout of data selected in the user routine TRDUMP for the nodal position 6 at every time step; these data provide the instantaneous values of the fuel and coolant temperatures, reactor power and neutron multiplication factor throughout the transient simulation and are listed for the periods 0 to 0.524 s and 1.109 to 1.127 s. During the latter period, the power reaches its maximum value of 2.95 MW at time 1.120 s. At that time, the fuel surface temperature has reached 415.9 K whereas the mean coolant temperature has increased to only 316 K.

Graphs of some of the major variables are shown in Figures 2 to 5; the data were obtained from the user dump file specified in the JCL (Appendix C3). The graphs were produced by executing the plot program of Turner [1982], using the catalogued procedure PROGRUN.

7.6 Description of Calculated Behaviour

Figure 2 illustrates the effect of vaporisation on both the power and excess reactivity of the core throughout the transient. It can be seen that a significant contribution from void formation does not arise before the time of peak power, and that after this time the reactivity feedback from this phenomenon becomes the major component. These predictions are in good agreement with the experimental data [Dalton 1983a] and support the assumptions made in the analysis of the SPERT II transients by Connolly [1977].

Figures 3, 4 and 5 show the predicted mass flows, vapour generation rates and void ratios at seven equally spaced nodal points along the fuelled length of the channel. It can be seen that up to the time of the peak power ($t \sim 1.1$ s), there is no vaporisation (Figure 4), and that no movement is induced in the coolant (Figure 3). The rapid increase in the vaporisation rate after this time is uniform along the channel (Figure 4) and the vapour generation forces the coolant out of both ends of the channel (Figure 3); the vapour generation rates reach a maximum then decrease as the reactor power passes through its peak value. This behaviour is mirrored by the outward flow at both ends of the flow path. As the core power decreases, a point is reached at which the flow direction at the inlet end (bottom) of the channel is reversed; cool liquid then begins to move into the flow path which leads progressively to the reduction of the vaporisation rate, and eventually causes condensation at increasing rates up the channel, a maximum rate being reached at successive intervals of time at adjacent nodal points. The condensation continues at a decreasing rate until all the vapour in the channel has disappeared.

The void ratios along the channel continue to rise for some time after the peak vaporisation rate (Figure 5), the reduction in the rate of the latter being reflected in the reduced rate of increase of the void ratios. The void ratios eventually reach a peak then fall as a result of the incidence of condensation at each nodal point in the sequence. The condensation produces a net flow of coolant up the channel, the differential rates of flow resulting from the different rates of condensation along the channel. When all the vapour has been condensed (Figure 5), the coolant is left with a residual uniform flow rate up the channel which drops steadily as the transient dies away.

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10. NOTATION

SI units are used for all variables.

Description	Symbol
Heat capacity per unit surface area	A
Flow area of flow path	a
Core reactivity feedback coefficients:	
fuel expansion plus Doppler broadening	B_1
neutron temperature	B_2
coolant expansion	B_3
Specific heat	c
Precursor concentrations	C_i
Quality of coolant (non-equilibrium)	C
Equivalent diameter of coolant channel	De
Energy flux of mixture	E
Frictional pressure gradient	F
Acceleration due to gravity	g
Mass velocity	G
Heat transfer coefficient	h
Enthalpy	H
Multiplication factor for core flux	k
Pressure loss coefficient	Ke
Prompt neutron lifetime	ℓ
Equivalent length of flow path	L
Momentum flux of mixture × flow area	M
Number of delayed neutron groups	n_β
Pressure	P
Heated perimeter of fuel	p
Prandtl number	Pr
Heat flux at fuel surface	q
Power generated per unit heated surface area	Q
Mean bubble radius	R
Universal gas constant	R_u
Reynolds number	Re
Entropy	s
Half fuel plate separation	S
Temperature	T
Real time	t
Velocity	u

Description	Symbol
Mass flow rate	W
Vector whose components are W, P, H and C	X
Vertical height	y
Axial distance along flow path	z
Void fraction in coolant	α
Delayed neutron fraction	β
Fission energy release	ξ
Thermal conductivity	κ
Vapour generation rate in coolant	Γ
Relaxation constants of delayed neutrons	λ_i
Constant in vapour generation formula	λ_N
Viscosity	μ
Reactor power	ϕ
Material density	ρ
Angle of elevation	θ
Surface tension	σ
Asymptotic period of power transient	τ_o
Spatial weighting of void reactivity	ω
Thickness of superheated water layer	χ
Mass flow rate of the vapour	Λ

Subscripts

F	Fuel mean	T	Total
FS	Fuel surface	V	Vapour
L	Bulk liquid	X	Superheated region
NB	Nucleate boiling	o	Time zero
S	Saturation		

TABLE 1

IDENTIFICATION OF THE HEAT TRANSFER OPTIONS

THT value	Correlation	
1	Forced convection	Dittus-Boelter [1930]
2	Forced convection	Colburn [1933]
3	Forced convection	Sieder-Tate [1936]
4	Forced convection	Kays [1966]
5	Conduction	Bayley et al. [1977]
6	Surface boiling	Forster and Zuber [1955]
7	Flow boiling	Bergles and Rohsenow [1964]
8	Dryout	Redfield [1965]

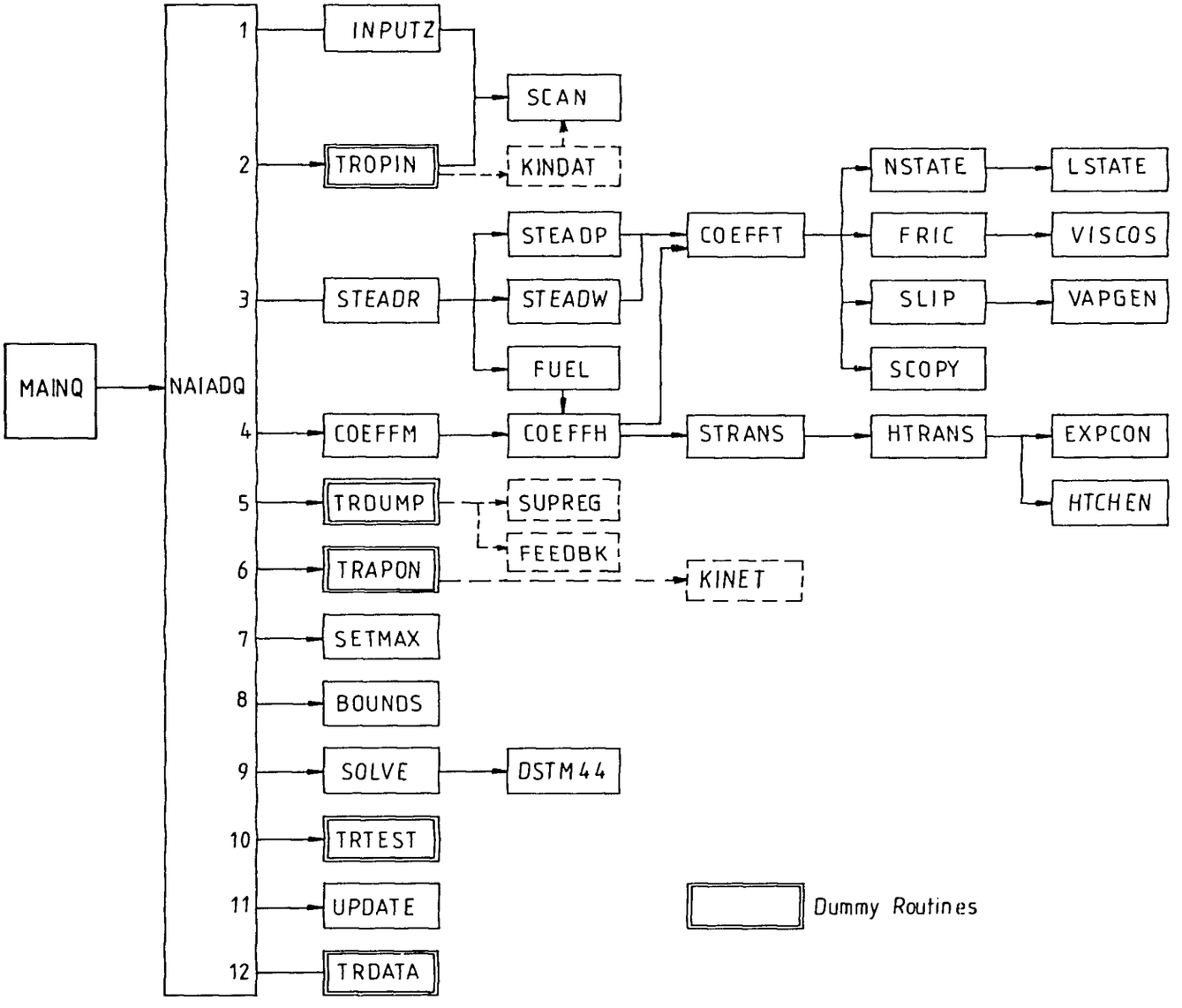

FIGURE 1. STRUCTURE OF THE NAIADQ CODE

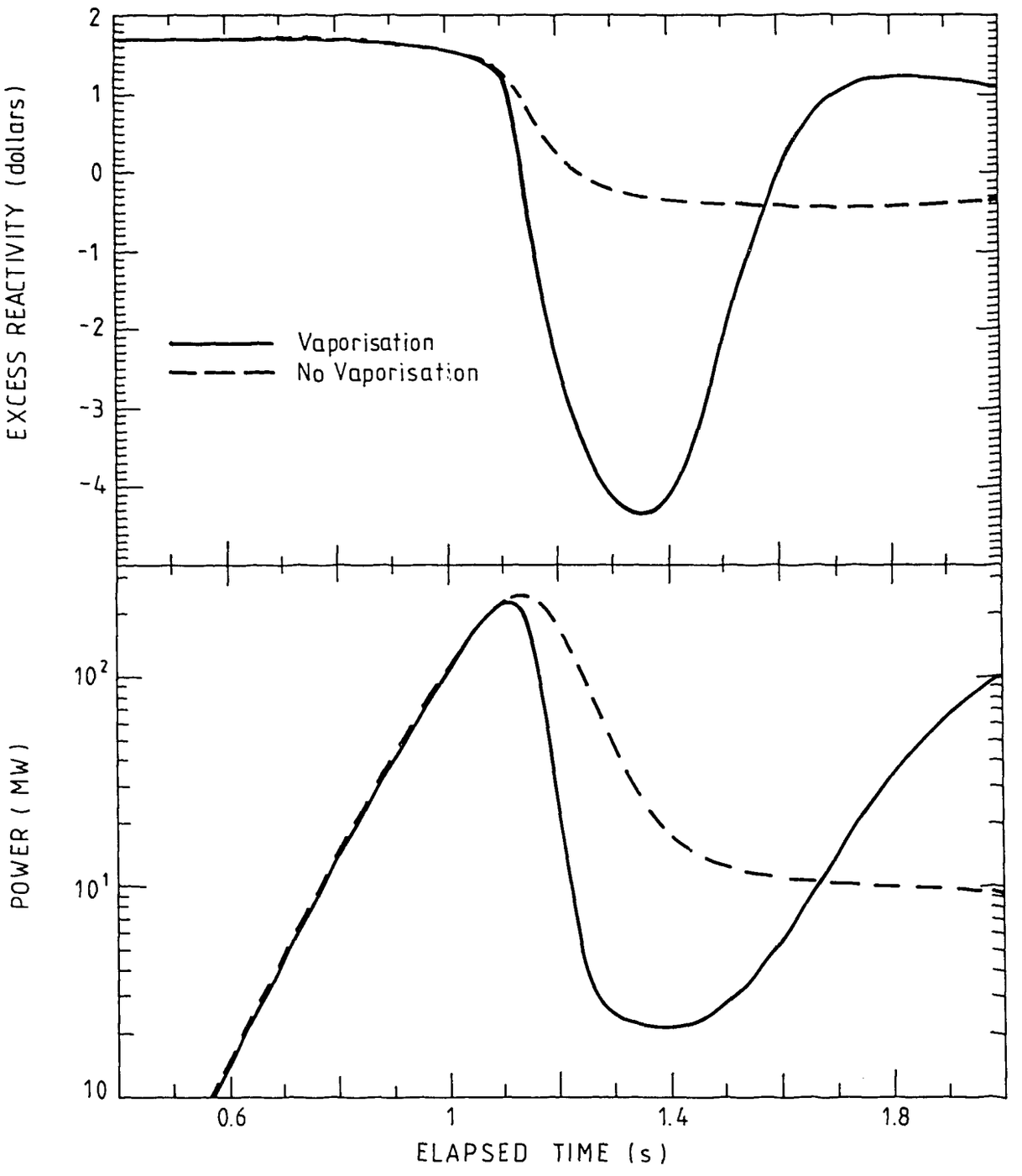

FIGURE 2. EFFECT OF VAPORISATION ON POWER AND EXCESS REACTIVITY

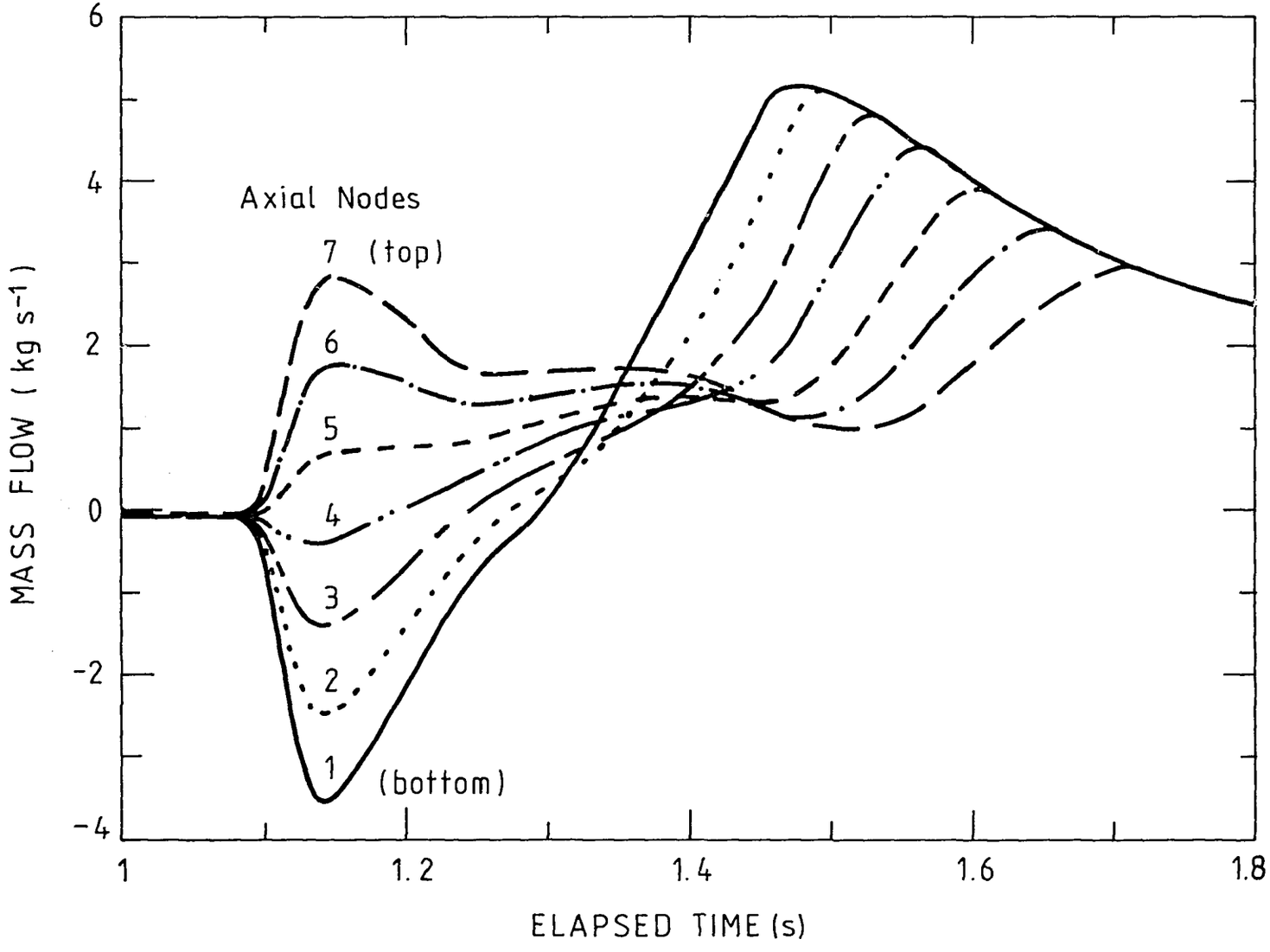

FIGURE 3. PREDICTED MASS FLOW RATES ALONG THE CHANNEL

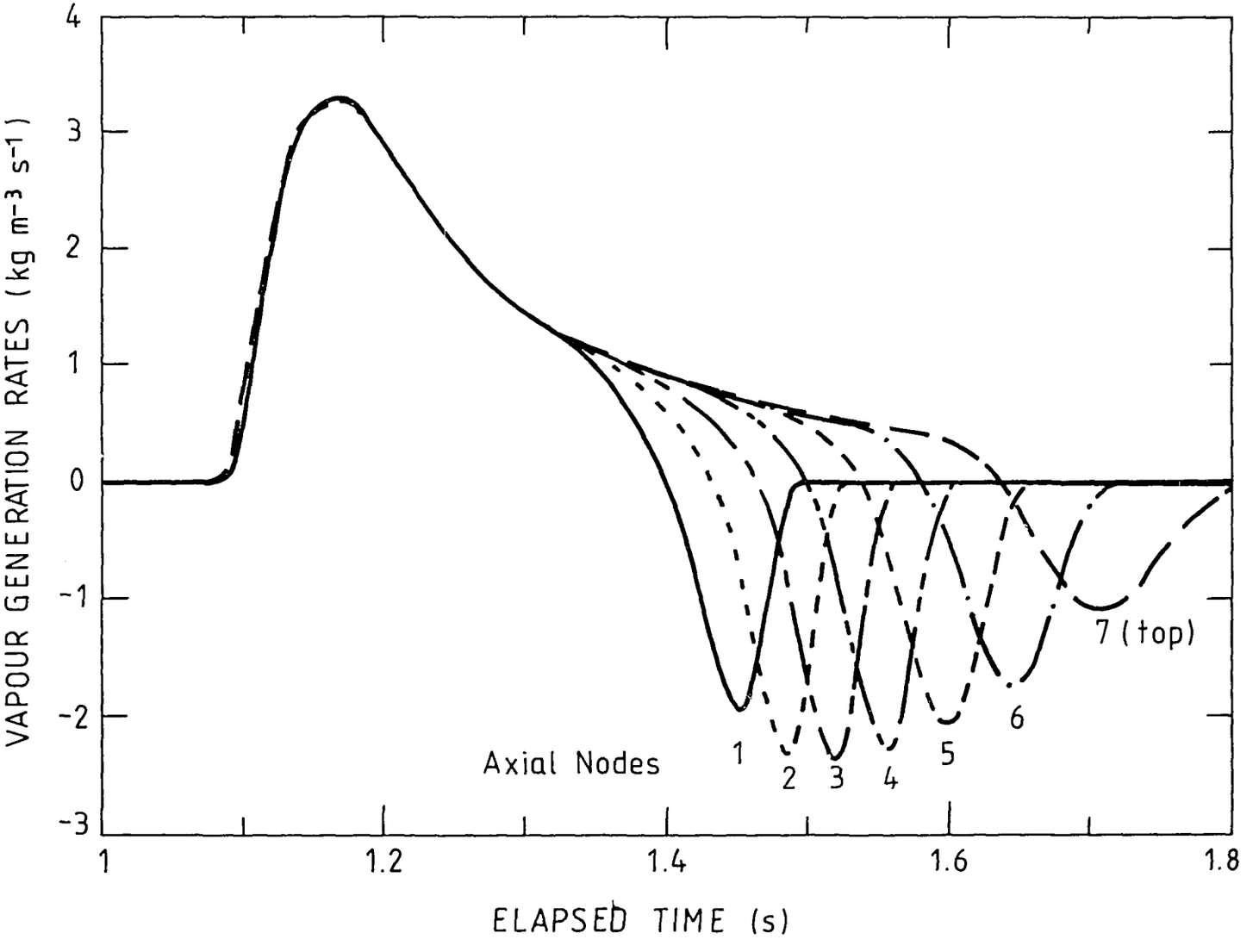

FIGURE 4. PREDICTED VAPORISATION RATES ALONG THE CHANNEL

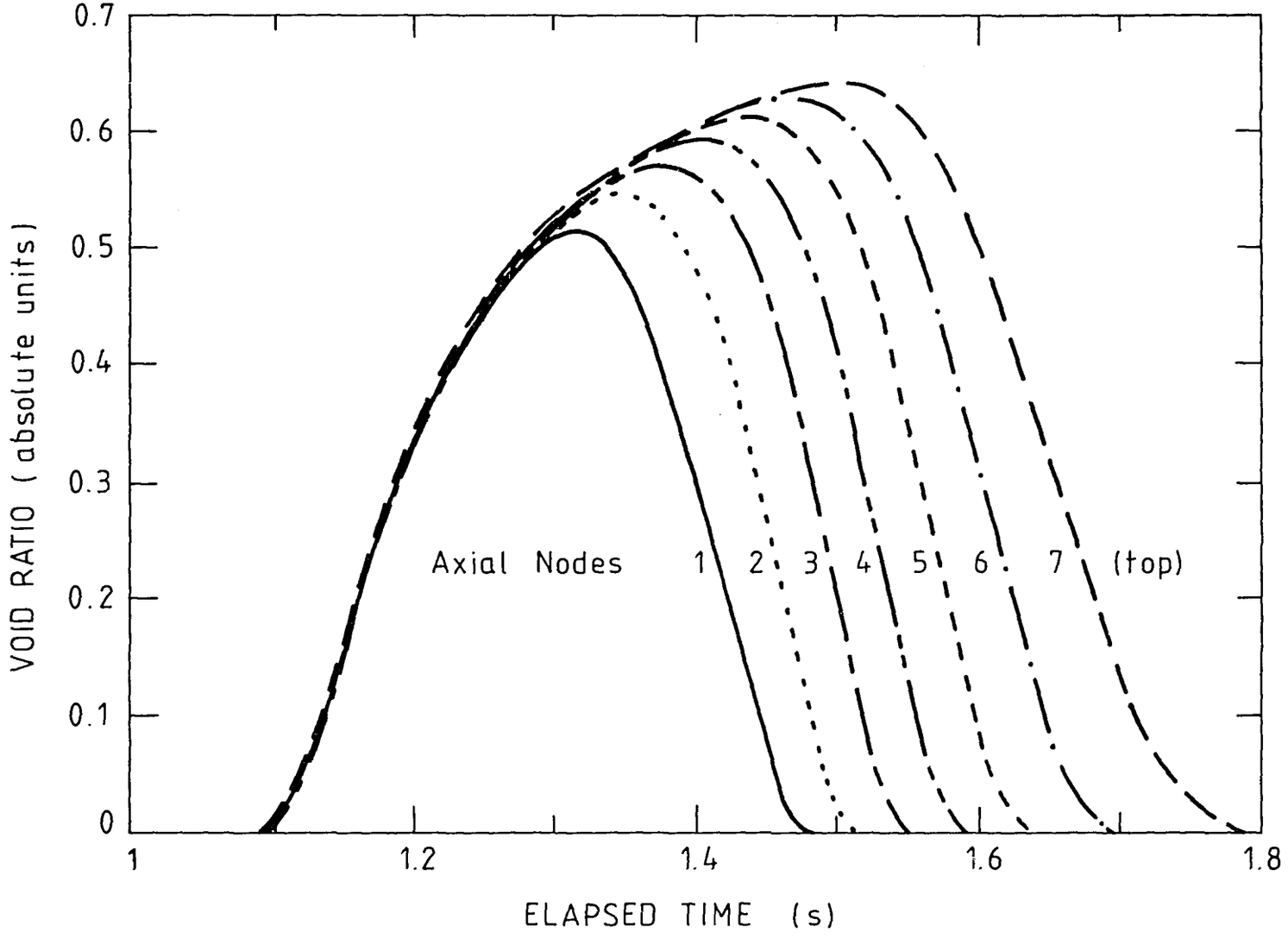

FIGURE 5. PREDICTED VOID RATIOS ALONG THE CHANNEL

APPENDIX A

DETAILS OF THE HEAT TRANSFER EQUATIONS

Within the NAIADQ code, the rate at which heat flux q is transferred from the fuel plate surface to the coolant is expressed in the form

$$q = h(T_{FS} - T_L)$$

The options for the surface heat transfer coefficient h representing the different regimes of heat transfer are described below.

A1 ZERO AND LOW MASS FLOW

For zero or low mass flow (Re <2000), the heat transfer option is based on transient conduction [Bayley et al. 1977]. For an exponentially increasing surface temperature Te^{t/τ_0} and parallel plate geometry, the temperature variation in the coolant is given by

$$\frac{\partial^2 T}{\partial x^2} - \frac{\rho c}{\kappa \tau_0} T = 0$$

For the boundary conditions $\frac{dT}{dx} = 0$, $T = T(0,t)$ at $x = 0$ and $T = T(S,t)$ at $x = S$; this gives an expression for h

$$h = \kappa B^2 S/(BS/\tanh BS - 1)$$

where $$B = \sqrt{\frac{\rho c}{\kappa \tau_0}}$$

A2 FORCED CONVECTION

When the flow of the coolant is turbulent (Re >2000), forced convective heat transfer becomes significant. Several options for h are available in NAIADQ, all of which are based on empirical correlations for single phase flow in cylindrical pipes. They are applicable over the Prandtl number range 0.5 to 120, Reynolds number range 2000 to 10^7, and L/De > 50. All options are evaluated at each time step, and the largest of these is used in the calculation. The following options are available:

(i) Modified Dittus-Boelter [1930]

Bergles and Rohsenow [1964], on the basis of their own research and that of Sparrow and Lin [1963] and Allen and Eckert [1964], showed that the original steady state correlation of Dittus-Boelter [1930] was ten per cent too low; they proposed

$$h = 0.025 \frac{\kappa_L}{D_e} \left\{ \frac{G\ De}{\mu_L} \right\}^{0.8} \left\{ \frac{\mu_L\ c_L}{\kappa_L} \right\}^{0.4}$$

(ii) Colburn [1933]

$$h = 0.023 \frac{\kappa_L}{De} \left\{ \frac{G\ De}{\mu_L} \right\}^{0.8} \left\{ \frac{\mu_M\ c_L}{\kappa_L} \right\}^{1/3}$$

where μ_M is evaluated at the film temperature

$$T_M = (T_L - T_{FS})/2$$

(iii) Seider-Tate [1936]

$$h = 0.027 \frac{\kappa_L}{De} \left\{ \frac{G\ De}{\mu_L} \right\}^{0.8} \left\{ \frac{\mu_L\ c_L}{\kappa_L} \right\}^{1/3} \left(\frac{\mu_L}{\mu_{FS}} \right)^{0.4}$$

where μ_{FS} is evaluated at fuel surface temperature.

(iv) Kays [1966]

$$h = 0.023 \frac{\kappa_L}{De} \left\{ \frac{G\ De}{\mu_L} \right\}^{0.83} \left\{ \frac{\mu_L\ c_L}{\kappa_L} \right\}^{0.5}$$

which is a variation of the Dittus-Boelter correlation.

NOTE: All variables except those specified are determined for the bulk coolant temperature T_L.

A3 SURFACE BOILING

A model for heat transfer in pool boiling, based on the turbulence produced in the superheated liquid boundary adjacent to the heated surface by bubble dynamics, was formulated by Forster and Zuber [1955]. This correlation, which gave good agreement with experimental data of Dergarabedian [1953], was derived from a dimensional analysis of experimental data for n-pentane, benzene, ethanol and water and has the form

$$Nu = 0.0015\ Re^{0.62}\ Pr^{0.33}$$

where Re, Pr and Nu, the Reynolds, Prandtl and Nusselt numbers for the flow system associated with bubble agitation in the superheated layer, are given by the dimensionless expressions:

$$Re = \left\{ \frac{\rho_L \kappa_L}{\mu_L} \right\} \left\{ \frac{\Delta T_S^2 \pi \rho_L c_L}{H_{LV}^2\ \rho_V^2} \right\}$$

$$Nu = q_{NB} \left\{ \frac{4\sigma^2 \rho_L}{\kappa_L^2 \Delta P^3} \right\}^{\frac{1}{4}} \left\{ \frac{\pi \rho_L c_L}{H_{LV}^2 \rho_V^2} \right\}^{\frac{1}{2}}$$

and $$Pr = \mu_L C_L / \kappa_L$$

which reduces to an expression for the heat flux

$$q_{NB} = H_{NB}(T_{FS} - T_S)$$

where $$H_{NB} = 1.22 \times 10^{-3} \left\{ \frac{\kappa_L^{0.8} c_L^{0.45}}{\mu_L^{0.3}} \right\} \left\{ \frac{\Delta T_S \rho_L^2 \Delta P_S^3}{H_{LV} \rho_V \sigma_L^2} \right\}^{\frac{1}{2}}$$

When used in the NAIADQ code, the heat transfer coefficient must be specified in terms of the difference between the heated surface and mean coolant temperature, hence:

$$h = H_{NB} \left\{ \frac{T_{FS} - T_S}{T_{FS} - T_L} \right\}$$

A4 FORCED CONVECTION SURFACE BOILING HEAT TRANSFER

For low wall superheat under turbulent flow conditions, the heat transfer is governed by forced convection. At moderate wall superheat, heat transfer is dependent on the combined effects of forced convection and surface boiling. At higher wall superheat, the variation with fluid velocity associated with forced convection seems to disappear, being replaced by a single curve representative of fully developed pool boiling, where the heat transfer depends only on the degree of wall superheating. Bergles and Rohsenow [1964] determined an interpolation formula which satisfies the characteristics of the boiling curve in the intermediate region where the heat flux for flow boiling q_{FB} in the transition region between that for forced convection q_{FC} and nucleate boiling q_{NB} is given by

$$q_{FB} = q_{FC} \left[1 + \frac{q_{NB}}{q_{FC}} \left(1 - \frac{q_{NBi}}{q_{NB}} \right)^2 \right]^{\frac{1}{2}}$$

where q_{NBi} is the boiling heat flux at incipient boiling and is obtained from the relationship

$$q_{NBi} = 1.806 \times 10^{-4} \, p^{1.156} \, (T_{FS} - T_S)^{2.83/p^{0.0234}}$$

The intersection of this curve with the forced convection heat transfer curve gives the degree of superheat required before boiling commences.

A5 DEPARTURE FROM NUCLEATE BOILING

The correlation given by Redfield [1965], based on that of Bernath [1960], was used to determine the transient critical heat flux at which a departure from nucleate boiling (DNB) is predicted. It is assumed that the heat transfer mechanism is convective through the turbulent, two-phase mixture in the superheated layer and is given by

$$q_{crit} = h_{crit}(T_{FS,crit} - T_L) \exp(0.00425/\tau_o)$$

where $T_{FS,crit} = 57(\ell n\ P - 8.84) - 54P/(P + 10^5)$

and $h_{crit} = 7 \times 10^4 + 187\ \mu/De^{0.6}$

APPENDIX B

BOUNDARY CONDITIONS

B1 FORM OF BOUNDARY CONDITIONS

For a flow path with boundaries defined by nodes 1 and n, the boundary conditions at these nodes for pressure and flow are expressed by a control parameter ψ, where

$$\psi_1' = P_1' \text{ or } W_1'$$

and

$$\psi_n' = P_n' \text{ or } W_n'$$

The boundary conditions for enthalpy η, and quality ζ, are given by

$$\eta_1' = H_1' \qquad \text{if } W_1 > 0$$

$$\zeta_1' = C_1'$$

and

$$\eta_n' = H_n' \qquad \text{if } W_n < 0$$

$$\zeta_n' = C_n'$$

B2 DETAILED SPECIFICATION

For pressure or flow control, there are two options using i to denote either 1 or n; the boundary conditions are given by

(i) P_i' (or W_i') = P_i (or W_i) - constant

or

(ii) P_i' (or W_i') = $P_i(t)$ (or $W_i(t)$) - explicit form (time-dependent)

There are three options for enthalpy and quality, all of which can be expressed in the general form, e.g. for enthalpy:

$$H_i' = \eta_i' + (H_i - \eta_i)\,\phi'/\phi$$

where ϕ = max (0, 1 - r/S), r is the distance travelled by the flow particle from the terminal node into the flow path.

The three options are as follows:

(a) Integral flow

$$\eta_i' = \eta_i = \eta_o \quad - \text{ constant}$$

S = distance travelled by a flow particle out of flow path since the last change in flow direction.

(b) Mean node

$$\eta_i' = \eta_i = \eta_o = \text{constant}$$

$$S = (z_i + z_j)/2$$

(c) Explicit

$$\left.\begin{aligned} \eta &= \eta(t) \\ S &= (z_i + z_j)/2 \end{aligned}\right\} \text{ [Turner and Trimble 1978]}$$

For options (b) and (c)

$j = 2$ if $i = 1$, or

$j = n - 1$ if $i = n$

The selection of the various options is made on the basis of a combination of the standard input data (Section 6.5); LBC is selected for pressure or flow control and LWP for enthalpy and quality continuity. The more complex explicit description, option (c), in terms of time-dependent properties of the coolant, is coded into the calculations via the routine TRAPON (Section 5.2).

APPENDIX C

PARTIAL LISTING FOR THE SAMPLE PROBLEM CALCULATIONS

C1 INPUT DATA

```
 NAME OF USER'S DATA SET: AWD.SPERT.DUMP
 DATA SET ON FORTRAN LOGIC UNIT NUMBER 8

 RUN 13: AMBIENT TEMPERATURE, ATMOSPHERIC PRESSURE, ZERO MASS FLOW

 TIME STEP CONTROLS
SMIN 1.D-6 SMAX 2.D-1  SINC 2.D0
TSFP 3 TMAX 3
CTAR .01  CMAX .02
 VAPOUR GENERATION PARAMETERS
ALAM 3.D-4  ALPHO 1.D-4
 FUEL CHANNEL DATA
11 NODES
SLIP 11*1  FRIC 11*1 (ALL HOMOGENEOUS)
NS 6 NP 100
Z 0 0.1 0.185(.087)0.707 0.792 .892
Y 0 0.1 0.184(.087)0.707 0.792 .892
DE 2*0.722 7*0.00463 2*.0722
A  2*0     7*0.00282 2*0
SR 11*2.54D-6
 DATA FOR POWER DISSIPATION
POWER 1.D0
HP 2*0 7*2.42 2*0
CP 2*0 7*1.74D3 2*0
HF 2*0 7*2.18E5 2*0
PD 0 0 7*1 0 0
 BOUNDARY CONDITIONS
LWP IN H C 2 OUT H C 2
LBC IN P 2   OUT P 2
 INITIAL COOLANT CONDITIONS
W 0
C 0.D0
P  1.1D5 1.0902D5 1.0819D5 1.0733D5 1.0648D5 1.0563D5
1.0479D5 1.0394D5 1.0308D5 1.0225D5 1.0128D5
H 11*9.24D4
 DATA TO BE WRITTEN ON FILE 1 OF DATA SET ON UNIT 8
UNIT 8 FILE 1
```

```
*
* INPUT DATA FOR REACTOR KINETICS AND FEEDBACK CALCULATIONS
*
* NEUTRON KINETICS DATA
*
  NEUTRON LIFETIME            ELL     4.8D-4
  NUMBER OF DELAYED GROUPS    NBETA    11
  TOTAL DELAYED FRACTION      BTALL   7.5D-3
  MAXIMUM POWER CHANGE        PEWR    5.0D1
  CHANNEL POWER               XNDO    1.D0
  EXCESS CORE REACTIVITY      EXCESK  1.84
  REACTIVITY RAMP             DKDT    0.0D0
  SHUTDOWN POWER              SOURCE  0.D0
  ASYMPTOTIC INVERSE PERIOD   BLO     1.3D1
  NUMBER OF FUEL ASSEMBLIES   CORE    6.8D1
*
* REACTIVITY COEFFICIENTS
*
  FUEL EXPANSION              EXPAN   2.1D-5
  DOPPLER EFFECT              FDOPL   0.0D0
  NEUTRON SPECTRUM EFFECT     CSPEC   3.1D-5
  COOLANT EXPANSION           CRHO    2.1D-3
  FLUX WEIGHTING FACTOR       BCOND   2.7D-1
```

C2 USER ROUTINES

```
      SUBROUTINE TROPIN

      USER ROUTINES FOR SPECIFYING DETAILS OF TRANSIENT SIMULATION

      IN THIS SAMPLE PROBLEM TRANSIENT IS INITIATED BY STEP INCREASE
      IN EXCESS CORE REACTIVITY AT TIME ZERO.  DATA FOR THE NEUTRONICS
      AND FEEDBACK CALCULATIONS ARE INPUT VIA THE ROUTINE KINDAT

      SELECTED DATA SPECIFIED IN CALL TO TDUMP ARE WRITTEN ON A
      DUMP FILE THE HEADING OF WHICH IS WRITTEN BY A CALL TO WDUMP

      NEUTRON KINETIC CALCULATIONS ARE DONE BY A CALL TO KINET

      REACTIVITY FEEDBACK CALCULATIONS, BY A CALL TO FEEDBK

 CINSERT R8,STEP,STATE,IGEOM,FLOW,POW$,TEMPS,KINFED,EXPAND,HEADS
      IMPLICIT REAL*H (A-H,O-Z)                                          R8
      COMMON /STEP/ TIME,DELT,SMIN,SMAX,SINC,TSEP,TMAX,CTAR,CMAX,CNOW    STEP
      COMMON /STATE/ W(52),P(52),H(52),C(52),                            STATE
     &  HSL(52),HSLP(52),HSV(52),HSVP(52),                               STATE
     &  RSL(52),RSLP(52),RSV(52),RSVP(52),                               STATE
     &  SSL(52),SSV(52),TS(52),TSP(52),                                  STATE
     &  HL(52),HLP(52),HLH(52),HLC(52),                                  STATE
     &  HV(52),HVP(52),HVH(52),HVC(52),                                  STATE
     &  RL(52),RLP(52),RLH(52),RLC(52),                                  STATE
     &  RV(52),RVP(52),RVH(52),RVC(52),                                  STATE
     &  TL(52),TLP(52),TLH(52),TLC(52),                                  STATE
     &  TV(52),TVP(52),TVH(52),TVC(52),                                  STATE
     &  R(52),RP(52),RH(52),RC(52),DOTR(52),                             STATE
     &  AL(52),ALP(52),ALH(52),ALC(52),ZX(52),ACR(52)                    STATE
      COMMON /IGEOM/ N                                                   IGEOM
      COMMON /FLOW/ UL(52),UV(52),XF(52),VF(52),FF(52),GAM(52),          FLOW
     &  AM(52),AMW(52),AMP(52),AMH(52),AMC(52),DOTAM(52),                FLOW
     &  AE(52),AEW(52),AEP(52),AEH(52),AEC(52),DOTAE(52),                FLOW
     &  WV(52),WVM(52),WVP(52),WVH(52),WVC(52),DOTWV(52),                FLOW
     &  VG(52),VGW(52),VGP(52),VGH(52),VGC(52),DOTVG(52)                 FLOW
      COMMON /POW$/ DZN(52),PGENP(9),THT(52),HT(52),FLUX(52),PTCT,PGEN   POW$
      COMMON /TEMPS/ CT(52),CTS(52),TFC(52),TFS(52)                      TEMPS
      COMMON /KINFED/ REACT1,REACT2,REACT3,REACT4,RACT,PERIOD,BL,        KINFED
     &ELL,BETALL,BETA(11),XLAM(11),PWER,XNDO,XPCO(11),EXCESK,            KINFED
     &DKDT,SOURCE,XND,XPC(11),ENERGY,TIMECH,BLO,CRHO,CSPEC,EXPAN,        KINFED
     &BCOND,PCORE,DKDTO,ENRE,BEXP,BFBK,NBETA                             KINFED
      COMMON /EXPAND/ CTB(50),RBOIL(50),HTCO(50),RSUP(50),XSRAT(50),     EXPAND
     &TMB(50),RSTAN(50),BCR(52),TBOIL                                    EXPAND
      COMMON /HEADS/ HEAD(10),DAY(3),TIM(6),NDAY,ITIM                    HEADS

      SPECIFICATION OF COMMON BLOCKS REQUIRED FOR USER ROUTINES

      DIMENSION NW(2),G(11,5)

      INTEGER HEAD (31) /'SAMPLE DUMP FILE'/

      USER'S INPUT FOR DUMP FILE

      IC=73
      CALL SCAN(1,1,IC,NW,2)
      NU=NW(1)
      NFILE=NW(2)
      CALL WDUMP(NU,NFILE,HEAD)

      INPUT OF NEUTRONICS AND REACTIVITY FEEDBACK DATA                   A
```

```
      CALL KINDAT
      RETURN

      ENTRY TRDUMP(IPRINT)
      IF(TIME.EQ.0.D0) GO TO 4
      FACTOR=XND/XNDO
      BL=DLOG(FACTOR)/DELT
      PERIOD=1/BL
      XNDO=XND
      ENPR-ENERGY*BLO/XND
    4 CONTINUE
       REACTIVITY FEEDBACK CALCULATIONS
      CALL FEEDBK(INPRINT,NS)
      PGEN=XND
      POW=PCORE*XND
      RDOLL=EXCESK/BETALL
      SELECTED PRINTOUT OF DATA AT EACH TIME STEP
      THESE DATA ARE USED FOR MONITORING THE COURSE OF THE TRANSIENT
      NS IS THE NODAL POSITION OF SELECTED DATA; SPECIFIED AS INPUT
      WRITE(3,8) TIME,TFS(NS),CT(NS),POW,ENPR,RDOLL,DENS,HT(NS),THT(NS)
      SPECIFICATION OF DATA RECORDS TO BE WRITTEN ON THE DUMP FILE
      CALL TDUMP(NU,TIME,1,W,N,TFS,N,CTS,N,CT,N,HT,N,H,N,P,N,C,N,AL,N,
     &VG,N,XSRAT,N,EXCESK,1,REACT1,1,REACT2,1,REACT3,1,DELT,1)
      RETURN

      ENTRY TRAPON
      DTRY=DELT
      NEUTRON KINETICS CALCULATION
      CALL KINET(ELL,BETALL,BETA,XLAM,PEWR,G,XNDO,XPCO,DTRY,
     &EXCESK,DKDT,SOURCE,XND,XPC,ENERGY,TIMECH)
      ENPR=(ENRE+ENERGY)*BLO/XND
      DELT=TIMECH
      RETURN

      ENTRY TRDATA
      OUTPUT OF TOTAL ENERGY GENERATED IN THE TRANSIENT
      WRITE(3,7) ENRE
      RETURN

    7 FORMAT(//,10X,'TOTAL ENERGY GENERATED = ',1PD12.4,/)
    8 FORMAT(' TIME',1PD11.4,' TFS, CT',0P2F8.2,' POWER',1PD11.3,
     &' ENPR',D11.3,' KEXC',D11.3.' AL',D11.3,' HT',D11.3,' THT',0PF4.1)

      END
```

C3 EXECUTIVE COMMANDS

```
  1     //AWDRUN01  JOB ('********/P22APLCA',N1),A.W.DALTON,
        //             CLASS=2,TIME=2
        ***ROUTE  PRINT VIEW
        ***JOBPARM  L=3
        ***

        ***
        ***      CATALOGUED PROCEDURE FOR EXECUTING THE COMPOSITE PROGRAM
        ***
        ***        'AAE.FORTLIB' DATASET OF LOCALLY WRITTEN FORTRAN
        ***         SUBROUTINES AVAILABLE ON THE AAEC SYSTEM
        ***        'PHYS.FORTLIB' DATASET OF LOCALLY WRITTEN FORTRAN
        ***         SUBROUTINES FOR PHYSICS TYPE PROBLEMS
        ***

        ***
   2    //  EXEC  NAIADCLG,PLIB='PHYS.FORTLIB',PLIB1='AAE.FORTLIB',VERSION=Q,
        //  REGGO=512K
  10    //SYSIN     DD *                GENERATED STATEMENT
  49    //GO.FT08F001 DD DSN=AWD.SPERT.DUMP,DISP=SHR
  50    //SYSIN     DD *                GENERATED STATEMENT

IEF142I AWDRUN01 PREP - STEP WAS EXECUTED - COND CODE 0000
IEF373I STEP /PREP    / START 82005.1642
IEF374I STEP /PREP    / STOP  82005.1642 CPU    0MIN 00.80SEC SRB    0MIN 00.06SEC
IEF142I AWDRUN01 FORT - STEP WAS EXECUTED - COND CODE 0000
IEF373I STEP /FORT    / START 82005.1642
IEF374I STEP /FORT    / STOP  82005.1642 CPU    0MIN 00.96SEC SRB    0MIN 00.14SEC
IEF142I AWDRUN01 LKED - STEP WAS EXECUTED - COND CODE 0000
IEF373I STEP /LKED    / START 82005.1642
IEF374I STEP /LKED    / STOP  82005.1643 CPU    0MIN 01.10SEC SRB    0MIN 00.33SEC
IEF142I AWDRUN01 CMPRS - STEP WAS EXECUTED - COND CODE 0000
IEF373I STEP /CMPRS   / START 82005.1643 CPU
IEF374I STEP /CMPRS   / STOP  82005.1643 CPU    0MIN 00.17SEC SRB    0MIN 00.02SEC
IEF272I AWDRUN01 GO    - STEP WAS EXECUTED -  COND CODE 0000
IEF373I STEP /GO      / START 82005.1643
IEF374I STEP /GO      / STOP  82005.1643 CPU    2MIN 53.15SEC SRB    0MIN 01.96SEC
IEF375I  JOB /AWDRUN01/ START 82005.1642
IEF376I  JOB /AWDRUN01/ STOP  82005.1643 CPU    2MIN 56.18SEC SRB    0MIN 02.51SEC

 LEVEL 20.1 (AUG 71)                          S/360  FORTRAN H

          COMPILER OPTIONS - NAME=  MAIN,OPT=02,LINECNT=55,SIZE=0000K,
                             SOURCE,EBCDIC,NOLIST,NODECK,LOAD,NOMAP,NOEDIT,NOID,NOXRE
               CINSERT MAINQ
   ISN 0002            CALL NAIADQ
   ISN 0003            STOP
   ISN 0004            END
```

TIME 0.0 POWER GENERATED 1.00000D+00 POWER TO COOLANT 1.00000D+00

NODE	VG	W	P	H	C	AL	R	T	TFS
1	0.0	0.0	1.10000D+05	9.2400D+04	0.0	0.0	997.91	295.17	295.17
2	0.0	0.0	1.0902D+05	9.2400D+04	0.0	0.0	997.91	295.17	295.17
3	0.0	0.0	1.0819D+05	9.2400D+04	0.0	0.0	997.91	295.17	295.17
4	0.0	0.0	1.0733D+05	9.2400D+04	0.0	0.0	997.91	295.17	295.17
5	0.0	0.0	1.0648D+05	9.2400D+04	0.0	0.0	997.91	295.17	295.17
6	0.0	0.0	1.0563D+05	9.2400D+04	0.0	0.0	997.91	295.17	295.17
7	0.0	0.0	1.0478D+05	9.2400D+04	0.0	0.0	997.91	295.17	295.17
8	0.0	0.0	1.0393D+05	9.2400D+04	0.0	0.0	997.91	295.17	295.17
9	0.0	0.0	1.0307D+05	9.2400D+04	0.0	0.0	997.91	295.17	295.17
10	0.0	0.0	1.0224D+05	9.2400D+04	0.0	0.0	997.91	295.17	295.17
11	0.0	0.0	1.0126D+05	9.2400D+04	0.0	0.0	997.90	295.17	295.17

TIME 0.0	TFS, CT	295.17	295.17	POWER	6.800D+01	ENPR	1.350D-05	KEXC	1.840D+00
TIME 1.0000D-06	TFS, CT	295.17	295.17	POWER	6.801D+01	ENPR	4.050D-05	KEXC	1.840D+00
TIME 3.0000D-06	TFS, CT	295.17	295.17	POWER	6.801D+01	ENPR	9.449D-05	KEXC	1.840D+00
TIME 7.0000D-06	TFS, CT	295.17	295.17	POWER	6.803D+01	ENPR	2.025D-04	KEXC	1.840D+00
TIME 1.5000D-05	TFS, CT	295.17	295.17	POWER	6.806D+01	ENPR	4.183D-04	KEXC	1.840D+00
TIME 3.1000D-05	TFS, CT	295.17	295.17	POWER	6.812D+01	ENPR	8.497D-04	KEXC	1.840D+00
TIME 6.3000D-05	TFS, CT	295.17	295.17	POWER	6.825D+01	ENPR	1.711D-03	KEXC	1.840D+00
TIME 1.2700D-04	TFS, CT	295.17	295.17	POWER	6.850D+01	ENPR	3.430D-03	KEXC	1.840D+00
TIME 2.5500D-04	TFS, CT	295.17	295.17	POWER	6.899D+01	ENPR	6.849D-03	KEXC	1.840D+00
TIME 5.1100D-04	TFS, CT	295.17	295.17	POWER	7.000D+01	ENPR	1.361D-02	KEXC	1.840D+00
TIME 1.0230D-03	TFS, CT	295.17	295.17	POWER	7.202D+01	ENPR	2.686D-02	KEXC	1.840D+00
TIME 2.0470D-03	TFS, CT	295.17	295.17	POWER	7.616D+01	ENPR	5.229D-02	KEXC	1.840D+00
TIME 4.0950D-03	TFS, CT	295.17	295.17	POWER	8.477D+01	ENPR	9.945D-02	KEXC	1.840D+00
TIME 8.1910D-03	TFS, CT	295.17	295.17	POWER	1.034D+02	ENPR	1.819D-01	KEXC	1.840D+00
TIME 1.6383D-02	TFS, CT	295.17	295.17	POWER	1.474D+02	ENPR	3.146D-01	KEXC	1.840D+00
TIME 3.2767D-02	TFS, CT	295.17	295.17	POWER	2.715D+02	ENPR	5.049D-01	KEXC	1.840D+00
TIME 6.5535D-02	TFS, CT	295.17	295.17	POWER	7.627D+02	ENPR	7.385D-01	KEXC	1.840D+00
TIME 1.3107D-01	TFS, CT	295.17	295.17	POWER	4.941D+03	ENPR	9.234D-01	KEXC	1.840D+00
TIME 2.6214D-01	TFS, CT	295.17	295.17	POWER	1.816D+05	ENPR	9.830D-01	KEXC	1.840D+00
TIME 5.2429D-01	TFS, CT	295.33	295.21	POWER	7.671D+06	ENPR	9.844D-01	KEXC	1.839D+00
TIME 5.2429D-01	TFS, CT	295.33	295.21	POWER	2.852D+05	ENPR	9.886D-01	KEXC	1.839D+00

TIME 5.57648D-01 POWER GENERATED 4.19384D+03 POWER TO COOLANT 1.37447D+03

NODE	VG	W	P	H	C	AL	R	T	TFS
1	0.0	2.4559D-02	1.10000D+05	9.2400D+04	0.0	0.0	997.91	295.17	295.17
2	0.0	2.4559D-02	1.0902D+05	9.2400D+04	0.0	0.0	997.91	295.17	295.17
3	0.0	2.4559D-02	1.0819D+05	9.2595D+04	0.0	0.0	997.90	295.22	295.36
4	0.0	2.4569D-02	1.0734D+05	9.2598D+04	0.0	0.0	997.90	295.22	295.36
5	0.0	2.4580D-02	1.0648D+05	9.2598D+04	0.0	0.0	997.90	295.22	295.36
6	0.0	2.4591D-02	1.0563D+05	9.2598D+04	0.0	0.0	997.90	295.22	295.36
7	0.0	2.4601D-02	1.0478D+05	9.2598D+04	0.0	0.0	997.90	295.22	295.36
8	0.0	2.4612D-02	1.0392D+05	9.2598D+04	0.0	0.0	997.90	295.22	295.36
9	0.0	2.4623D-02	1.0307D+05	9.2598D+04	0.0	0.0	997.90	295.22	295.36
10	0.0	2.4633D-02	1.0224D+05	9.2402D+04	0.0	0.0	997.91	295.17	295.17
11	0.0	2.4634D-02	1.0126D+05	9.2400D+04	0.0	0.0	997.90	295.17	295.17

TIME 1.10904D+00 POWER GENERATED 4.1P307D+06 POWER TO COOLANT 2.38361D+06

NODE	VG	W	P	H	C	AL	R	T	TFS
1	0.0	-1.0106D+00	1.10009+05	9.2410D+04	0.0	0.0	997.91	295.17	295.17
2	0.0	-1.0105D+00	1.1159D+05	9.3561D+04	0.0	0.0	997.85	295.45	295.45
3	8.2098D-01	-1.0136D+00	1.1408D+05	1.5945D+05	5.0406D-06	7.4400-03	985.69	311.21	411.31
4	8.0406D-01	-6.9756D-01	1.1568D+05	1.5987D+05	4.9816D-06	7.259D-03	985.84	311.31	411.45
5	7.9924D-01	-3.9286D-01	1.1626D+05	1.5989D+05	4.9787D-06	7.221D-03	985.87	311.31	411.48
6	8.0936D-01	-9.2063D-02	1.1586D+05	1.5999D+05	5.0553D-06	7.354D-03	985.73	311.34	411.41
7	8.3538D-01	2.1269D-01	1.1447D+05	1.6018D+05	5.2195D-06	7.676D-03	985.40	311.38	411.24
8	8.7928D-01	5.3009D-01	1.1206D+05	1.6045D+05	5.4801D-06	8.217D-03	984.83	311.45	410.96
9	9.4526D-01	8.6989D-01	1.0853D+05	1.6083D+05	5.8617D-06	9.049D-03	983.97	311.54	410.55
10	0.0	1.2366D+00	1.0509D+05	9.4287D+04	0.0	0.0	997.81	295.62	295.62
11	0.0	1.2320D+00	1.0126D+05	9.2438D+04	0.0	0.0	997.90	295.18	295.18

TIME	1.1090D+00	TFS, CT	411.41	311.34	POWER	2.8600+08	ENPR	1.337D+00	KEXC	1.303D+00
TIME	1.1101D+00	TFS, CT	411.93	311.72	POWER	2.875D+08	ENPR	1.345D+00	KEXC	1.281D+00
TIME	1.1112D+00	TFS, CT	412.42	312.09	POWER	2.888D+08	ENPR	1.353D+00	KEXC	1.257D+00
TIME	1.1123D+00	TFS, CT	412.88	312.48	POWER	2.900D+08	ENPR	1.361D+00	KEXC	1.233D+00
TIME	1.1133D+00	TFS, CT	413.31	312.86	POWER	2.911D+08	ENPR	1.369D+00	KEXC	1.208D+00
TIME	1.1143D+00	TFS, CT	413.71	313.26	POWER	2.921D+08	ENPR	1.378D+00	KEXC	1.181D+00
TIME	1.1153D+00	TFS, CT	414.10	313.65	POWER	2.929D+08	ENPR	1.388D+00	KEXC	1.154D+00
TIME	1.1163D+00	TFS, CT	414.46	314.05	POWER	2.935D+08	ENPR	1.398D+00	KEXC	1.125D+00
TIME	1.1172D+00	TFS, CT	414.80	314.45	POWER	2.941D+08	ENPR	1.408D+00	KEXC	1.096D+00
TIME	1.1182D+00	TFS, CT	415.11	314.86	POWER	2.945D+08	ENPR	1.419D+00	KEXC	1.065D+00
TIME	1.1191D+00	TFS, CT	415.41	315.26	POWER	2.948D+08	ENPR	1.430D+00	KEXC	1.033D+00
TIME	1.1201D+00	TFS, CT	415.69	315.68	POWER	2.949D+08	ENPR	1.442D+00	KEXC	1.001D+00
TIME	1.1210D+00	TFS, CT	415.94	316.10	POWER	2.949D+08	ENPR	1.454D+00	KEXC	9.670D-01
TIME	1.1219D+00	TFS, CT	416.18	316.52	POWER	2.947D+08	ENPR	1.467D+00	KEXC	9.325D-01
TIME	1.1228D+00	TFS, CT	416.40	316.95	POWER	2.944D+08	ENPR	1.481D+00	KEXC	8.970D-01
TIME	1.1237D+00	TFS, CT	416.61	317.38	POWER	2.940D+08	ENPR	1.495D+00	KEXC	8.607D-01
TIME	1.1246D+00	TFS, CT	416.79	317.81	POWER	2.934D+08	ENPR	1.510D+00	KEXC	8.235D-01
TIME	1.1255D+00	TFS, CT	416.96	318.25	POWER	2.926D+08	ENPR	1.526D+00	KEXC	7.855D-01
TIME	1.1264D+00	TFS, CT	417.12	318.70	POWER	2.918D+08	ENPR	1.542D+00	KEXC	7.466D-01
TIME	1.1273D+00	TFS, CT	417.26	319.15	POWER	2.907D+08	ENPR	1.560D+00	KEXC	7.070D-01

TIME 1.12812D+00 POWER GENERATED 4.27556D+06 POWER TO COOLANT 3.54551D+06

NODE	VG	W	P	H	C	AL	R	T	TFS
1	-1.5650D-02	-3.4461D+00	1.1000D+05	9.3053D+04	7.7581D-10	1.199D-06	997.87	295.32	295.32
2	-3.9937D-01	-3.4440D+00	1.1174D+05	1.0374D+05	1.0597D-07	1.613D-04	997.10	297.88	297.88
3	2.9429D+00	-3.4167D+00	1.1402D+05	1.9475D+05	4.2599D-05	5.941D-02	930.91	319.63	416.88
4	2.9061D+00	-2.3684D+00	1.1676D+05	1.9471D+05	4.1800D-05	5.715D-02	933.15	319.62	417.28
5	2.8875D+00	-1.3482D+00	1.1797D+05	1.9453D+05	4.1471D-05	5.621D-02	934.10	319.58	417.44
6	2.8917D+00	-3.4140D-01	1.1773D+05	1.9461D+05	4.1705D-05	5.662D-02	933.70	319.60	417.39
7	2.9181D+00	6.6711D-01	1.1611D+05	1.9503D+05	4.2626D-05	5.850D-02	931.79	319.70	417.13
8	2.9616D+00	1.6953D+00	1.1312D+05	1.9570D+05	4.4073D-05	6.176D-02	928.50	319.86	416.65
9	3.0164D+00	2.7544D+00	1.0872D+05	1.9670D+05	4.6124D-05	6.672D-02	923.50	320.10	415.93
10	-3.5075D-01	3.8307D+00	1.0513D+05	1.0273D+05	8.4470D-08	1.361D-04	997.19	297.64	297.64
11	-1.4810D-02	3.8572D+00	1.0126D+05	9.3141D+04	6.8811D-10	1.149D-06	997.86	295.35	295.35

APPENDIX D

TABLES OF COMMON BLOCKS USED IN NAIADQ

The common blocks listed in Tables D1 to D11 contain all the variables of importance in the standard version of the NAIADQ code. All are available for inclusion in the FORTRAN subroutines written by the user. With NAIADCLG, the common blocks are copied into the FORTRAN source decks during the PREP stage, if a 'CINSERT' card is included [Trimble and Turner 1976]. By this means, the tedious process of duplicating common blocks and the concomitant possibility of mistakes are avoided. The format for the card would be, for example:

```
CINSERT EXPAND, STATE, ETC
```

TABLE D1

THE 'STATE' COMMON BLOCK

Variable & Dimensions	Description	Algebraic Symbol
W(52)	Mass flow rate	W
P(52)	Pressure	P
H(52)	Flow enthalpy	H
C(52)	Static	C
HSL(52)	Saturated liquid enthalpy	H_L
HSLP(52)		$\partial H_{SL}/\partial P$
HSV(52)	Saturated vapour enthalpy	H_{SV}
HSVP(52)		$\partial H_{SV}/\partial P$
RSL(52)	Saturated liquid density	ρ_{SL}
RSLP(52)		$\partial \rho_{SL}/\partial P$
RSV(52)	Saturated vapour density	ρ_{SV}
RSVP(52)		$\partial \rho_{SV}/\partial P$
SSL(52)	Saturated liquid entropy	S_L
SSV(52)	Saturated vapour entropy	S_V
TS(52)	Coolant saturation temperature	T_S
TSP(52)		$\partial T_S/\partial P$
HL(52)	Liquid enthalpy	H_L
HLP(52)		$\partial H_L/\partial P$
HLH(52)		$\partial H_L/\partial H$
HLC(52)		$\partial H_L/\partial C$
HV(52)	Vapour enthalpy	H_V
HVP(52)		$\partial H_V/\partial P$
HVH(52)		$\partial H_V/\partial H$
HVC(52)		$\partial H_V/\partial C$
RL(52)	Coolant density (single phase)	ρ_L
RLP(52)		$\partial \rho_L/\partial P$
RLH(52)		$\partial \rho_L/\partial H$
RLC(52)		$\partial \rho_L/\partial C$
RV(52)	Vapour density	ρ_V
RVP(52)		$\partial \rho_V/\partial P$
RVH(52)		$\partial \rho_V/\partial H$
RVC(52)		$\partial \rho_V/\partial C$
TL(52)	Coolant temperature	T_L
TLP(52)		$\partial T_L/\partial P$

Table D1 (cont'd.)

Variable & Dimensions	Description	Algebraic Symbol
TLH(52)		$\partial T_L/\partial H$
TLC(52)		$\partial T_L/\partial C$
TV(52)	Vapour temperature	T_V
TVP(52)		$\partial T_V/\partial P$
TVH(52)		$\partial T_V/\partial H$
TVC(52)		$\partial T_V/\partial C$
R(52)	Fluid density	ρ
RP(52)		$\partial\rho/\partial P$
RH(52)		$\partial\rho/\partial H$
RC(52)		$\partial\rho/\partial C$
DOTR(52)		$X\partial\rho/\partial X$

TABLE D2

THE 'BCONDX' COMMON BLOCK

Variable & Dimensions	Description	Algebraic Symbol
BCW(2)	Flow boundary condition	ψ_i
BCP(2)	Pressure boundary conditions	
BCH(2)	Enthalpy boundary conditions	η_i
BCC(2)	Quality boundary conditions	ξ_i

TABLE D3

THE 'POW$' COMMON BLOCK

Variable & Dimensions	Description	Algebraic Symbol
DSN(52)	Distance between adjacent nodes	$z_i - z_{i-1}$
PGENP(9)	Power generated in flow path	Q
THT(52)	Heat transfer indicator	THT
HT(52)	Fuel to coolant heat transfer coefficient	h
FLUX(52)	Fuel to coolant heat fluxes	q
PGEN	Total power to coolant	

TABLE D4

THE 'FLOW' COMMON BLOCK

Variable & Dimensions	Description	Algebraic Symbol
AM(52)	Momentum flux × area	M
AMW(52)		∂M/∂W
AMP(52)		∂M/∂P
AMC(52)		∂M/∂C
DOTAM(52)		X∂M/∂X
AR(52)	Coolant momentum	R
ARW(52)		∂R/∂W
ARP(52)		∂R/∂P
ARH(52)		∂R/∂H
ARC(52)		∂R/∂C
DOTAR(52)		X∂R/∂X
AE(52)	Coolant energy flux	E
AEW(52)		∂E/∂W
AEP(52)		∂E/∂P
AEH(52)		∂E/∂H
AEC(52)		∂E/∂C
DOTAE(52)		X∂E/∂X

Table D4 (cont'd.)

Variable & Dimensions	Description	Algebraic Symbol
WV(52)	Vapour mass flow	W_V
WVW(52)		$\partial WV/\partial W$
WVP(52)		$\partial WV/\partial P$
WVH(52)		$\partial WV/\partial H$
WVC(52)		$\partial WV/\partial C$
DOTWV(52)		$X\partial WV/\partial X$
VG(52)	Vapour mass generation rate	Γ
VGW(52)		$\partial\Gamma/\partial W$
VGP(52)		$\partial\Gamma/\partial P$
VGH(52)		$\partial\Gamma/\partial H$
VGC(52)		$\partial\Gamma/\partial C$
DOTVG(52)		$X\partial\Gamma/\partial X$

TABLE D5

THE 'STEP' COMMON BLOCK

Variable & Dimensions	Description
TIME	Time
DELT	Time step
SMIN	Minimum time step allowed
SMAX	Maximum time step allowed
SINC	Maximum time step increase
TSFP	Time at which full printout commences
TMAX	Maximum time specified for transit calculation
CTAR	Target fractional change
CMAX	Maximum fractional change
CNOW	Calculated fractional change in P, H

TABLE D6

THE 'GEOM' COMMON BLOCK

Variable & Dimensions	Description	Algebraic Symbol
Z(52)	Axial distance from end of flow path	z
Y(52)	Vertical height	y
DE(52)	Equivalent diameter of pipe	De
A(52)	Cross-sectional area of pipe	A
SR(52)	Surface roughness	ε
ORIKE(52)	Coefficient representing the sum of the local pressure losses	Ke
N	Number of nodes	n

TABLE D7

THE 'HEATS' COMMON BLOCK

Variable & Dimensions	Description	Algebraic Symbol
HP(52)	Heated wetted perimeter	P
CP(52)	Heated capacity of fuel	λ
HF(52)	Fuel centre to fuel surface heat transfer coefficient	h_f
PD(52)	Power distribution factor	Q/PGENP
PTC(52)	Power to coolant	

TABLE D8

THE 'EXPAND' COMMON BLOCK

Variable & Dimensions	Description
CTB(50)	Mean liquid temperature at time vapour generation begins
RBOIL(50)	Mean liquid density at time vapour generation begins
HTCO(50)	Heat content of liquid at time vapour generation begins
RSUP(50)	Density of superheated liquid adjacent to heated surface
XSRAT(50)	Thickness of superheated layer
THB(50)	Temperature of superheated liquid
RSTAN(50)	Mean density of liquid
BCR(52)	Intermediate variable in the calculation of vapour generation rate
RMIX(52)	Calculation of vapour generation rate mean density of vapour liquid mixture
RHOS	Mean liquid density at time zero
CTST	Mean liquid temperature at time zero

TABLE D9

THE 'HEADS' COMMON BLOCK

Variable & Dimensions	Description
HEAD(10)	Heading
DAY(3)	Date
TIM	Time
NDAY	Hexadecimal year and day number
ITIM	Integral time after midnight in hundredths of a second

TABLE D10

THE 'TEMP' COMMON BLOCK

Variable & Dimensions	Description	Algebraic Symbol
CT(52)	Bulk coolant temperature	T_L
CTS(52)	Water saturation temperature	T_S
TF(52)	Mean fuel temperature	T_F
TFS(52)	Fuel surface temperature	T_{FS}

TABLE D11

THE 'KINFED' COMMON BLOCK

Variable & Dimensions	Description
REACT1	Reactivity feedback from fuel expansion
REACT2	Reactivity feedback from coolant expansion
REACT3	Reactivity feedback from neutron temperature changes
REACT4	Reactivity feedback from vapour void formation
RACT	Total reactivity feedback
PERIOD	Instantaneous period
BLO	Asymptotic inverse reactivity period
ELL	Prompt neutron lifetime
BETALL	Total delayed neutron fraction
BETA(11)	Array of delayed neutron fractions
XLAM(11)	Array of precursor relaxation constants
PEWR	Maximum increase in reactor power in one time step
XNDO	Power at the beginning of the time step
XPCO(11)	Array of precursor concentrations at the beginning of a time step
EXCESK	Excess core reactivity at the beginning of a time step
DKDT	Instantaneous ramp rate of reactivity insertion
SOURCE	Shutdown power of the reactor
XND	Power level at the end of the time step

TABLE D11 (cont'd.)

Variable & Dimensions	Description
XPC(11)	Precursor concentrations at end of a time step
ENERGY	Energy generated at the time step
TIMECH	Time step size limited by the kinetics calculation
BL	Instantaneous inverse period
CRHO	Coolant density reactivity feedback coefficient
CSPEC	Neutron temperature reactivity feedback coefficient
EXPAN	Coefficient of expansion of the fuel
BCOND	Weighting factor for void reactivity feedback
CORE	Number of fuel assemblies in the reactor core
DKDTO	Ramp reactivity insertion rate at time zero
ENRE	Total energy generated up to this instant